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the 1990s, the number of people in the UK who are aged 65 and over has increased by 1.5 million, and the number of people aged 75 and over has increased by 1.2 million (Office for National Statistics 1999). The number of people aged 65 and over is projected to increase to 6.5 million by 2011, and the number of people aged 75 and over to 4.5 million (Office for National Statistics 1999).

There is a growing awareness of the need to develop services to meet the needs of older people, and a number of initiatives have been launched in the UK to address this need. The Department of Health has launched the 'Age Friendly' initiative, which aims to make the UK a more age-friendly country by 2010. The initiative is based on the principle that older people should be able to live independently and actively in their own homes, and that services should be developed to support them to do so.

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SECTION-1 FOREWORD, SCOPE AND PURPOSE

This document is submitted in compliance with the requirements of contract NAS 9-17877. It constitutes the Final Report for the "Tethered Gravity Laboratories Study" sponsored by National Aeronautics and Space Administration - Lyndon B. Johnson Space Center - Houston - Texas.

This work has been performed under responsibility of the Space Systems Group of AERITALIA-Turin-Italy, Principal Investigator : Dr. Pietro Merlina , Co-Investigators: Walter Bogo, Mauro Briccarello, Stefano Cesare, Fabrizio Lucchetti.

The numerical simulations related to the dynamics and control aspects of the study have been performed, as Subcontractor, by the Smithsonian Astrophysical Observatory - Cambridge-Massachusetts, Principal Investigator : Dr. Enrico C. Lorenzini, Co-Investigators : Mario Cosmo, David A. Arnold.

The work on the acceleration environment of the Space Station has been performed, as Subcontractor, by the University of Padua, Principal Investigator : Prof. Silvio Bergamaschi.

The scope of the study is to investigate ways of controlling the microgravity environment of the International Space Station by means of a tethered system. Four main study tasks have been performed.

In the Task-1, researchers have analyzed the utilization of tether systems to improve the lowest possible steady gravity level on the Space Station, and the tether capability to actively control the center of gravity position in order to compensate for activities that would upset the mass distribution of the Station. In Section-2 a summary is given of the work performed and of the major findings emerged. The complete study is reported in: "Active Center of Gravity Control", AERITALIA Task-1 Final Report, TG-RP-AI-021, November 1989.

The purpose of the Task-2 is to evaluate the whole of the experiments performable in a variable gravity environment, and the related beneficial residual accelerations, both for pure and applied research in the

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fields of Fluid, Materials and Life Science, so as to assess the relevance of a variable g-level laboratory. In Section-3 a synthesis is reported of this activity. The complete work can be found in: "Low Gravity Processes Identification", AERITALIA Task-2 Final Report, TG-RP-AI-001, February 1989.

In Section-4, it is reported the complete study on the "Tethered Variable Gravity Laboratory". This is the major task of the overall study. The use of a variable microgravity facility that would crawl along a deployed tether and expose experiments to varying intensities of reduced gravity is addressed. Several possible configurations for the variable-g laboratory have been analyzed, and the system has been tentatively defined in terms of conceptual configuration and technology requirements. Finally, a preliminary design at system level has been performed to investigate some unique features of this facility.

In Section-5, it is presented the study performed on the "Attitude Tether Stabilizer" concept. The stabilizing effect of ballast masses tethered to the Space Station has been investigated as a means to assist the Attitude Control System of the Station. In the context of the present study this task-4 has been addressed at the end of the two years contract, therefore the relevant analysis effort has been limited in time and extension. Nevertheless this concept has been discovered to have the potential for being an effective way of overcoming some difficulties in the design of the Attitude Control System of the Space Station.

After Section-6 (including the Appendices), finally in Section-7, it is enclosed the Final Report of the Smithsonian Astrophysical Observatory. SAO has performed an extensive work of simulation through the overall study period in order to assess basic dynamics and control aspects related to the concepts under investigation. We are indebted with SAO for the help in the overcoming the difficulties related to the distance between United States and Italy.

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SECTION - 2

SUMMARY OF THE "ACTIVE CENTER OF GRAVITY CONTROL" TASK

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2.1 INTRODUCTION

The availability of an environment with a very low level of acceleration is one of the reasons for building the Space Station from the science point of view. This is even more true for future industrial and commercial use of space. The most severe requirement on the acceptable acceleration level comes from the material processing community which regards a steady or low frequency acceleration of 1 micro-g as acceptable and one of 0.01 micro-g as desirable (in the frequency range from 0 to 0.01 Hz). This very strict requirement is largely exceeded by the International Space Station (ISS) specification which is 10 micro-g at all frequencies. The requirement drop quickly at higher frequencies and is 10 micro-g at 1 Hz and 1 milli-g at 100 Hz.

Sensitive experiments can be mechanically insulated from the high frequency acceleration sources with proper devices. Steady or very low frequency accelerations are rather difficult to deal with in this manner, so the only possible way of obtaining a good experimental environment lies in reducing the causes of the accelerations.

The objective of this work on the "Active Center of Gravity Control" is to investigate, the utilization of tether systems to improve the lowest possible steady gravity level on the ISS, and the tether capability to actively control the center of gravity position in order to compensate for activities that would upset the mass distribution of the Station.

Here, a summary is reported of the work performed and of the major findings emerged. For the complete technical analyses, please refer to: "Active Center of Gravity Control", AERITALIA Task-1 Final Report, TG-RP-AI-021, November 1989.

2.2

SPACE STATION ENVIRONMENT

From the phased program assembly configuration data it was possible to extract the relevant information for a definition of the steady or quasi-static micro-g environment on the ISS. Some assumptions were made in order to compute the accelerations. The two main ones are:

- Space Station in the nominal attitude position with all the solar panels perpendicular to the flight direction (worst case for drag).
- Max. attitude motion amplitude of 5 degrees and 0.02 degree/second as max. rate (worst case within the Space Station requirements).

The main sources of acceleration are :

- Atmospheric drag. Which causes a steady acceleration equal on all the points of the ISS directed approximately along the flight direction (X axis);
- Gravity gradient. The acceleration caused by the gravity gradient is almost steady (with little variations due to the orbital eccentricity) and depends on the distance from the ISS center of gravity (CG) along the local vertical and out of the orbital plane direction. On the laboratory modules this acceleration is directed mainly along the local vertical. In Figure 2.2-1 the relative positions of the U.S. laboratory and CG are shown. The elliptical line is the envelope of the room within which the CG should lie in order to limit the value of gravity gradient acceleration to 1 micro-g in the whole laboratory. The two dashed lines limit the portion of the laboratory which is within the 1 micro-g requirement in the OF2 and MB16 flights.
- Attitude motion. The acceleration due to the attitude motion is assumed to have a period which is a fraction of the orbital period (approximately one third) and depends on the distance from the CG, being so rather large on the European and Japanese modules.

All these disturbances are approximately of the same order of magnitude in the U.S. module being of the order of 0.3 to 1 micro-g.

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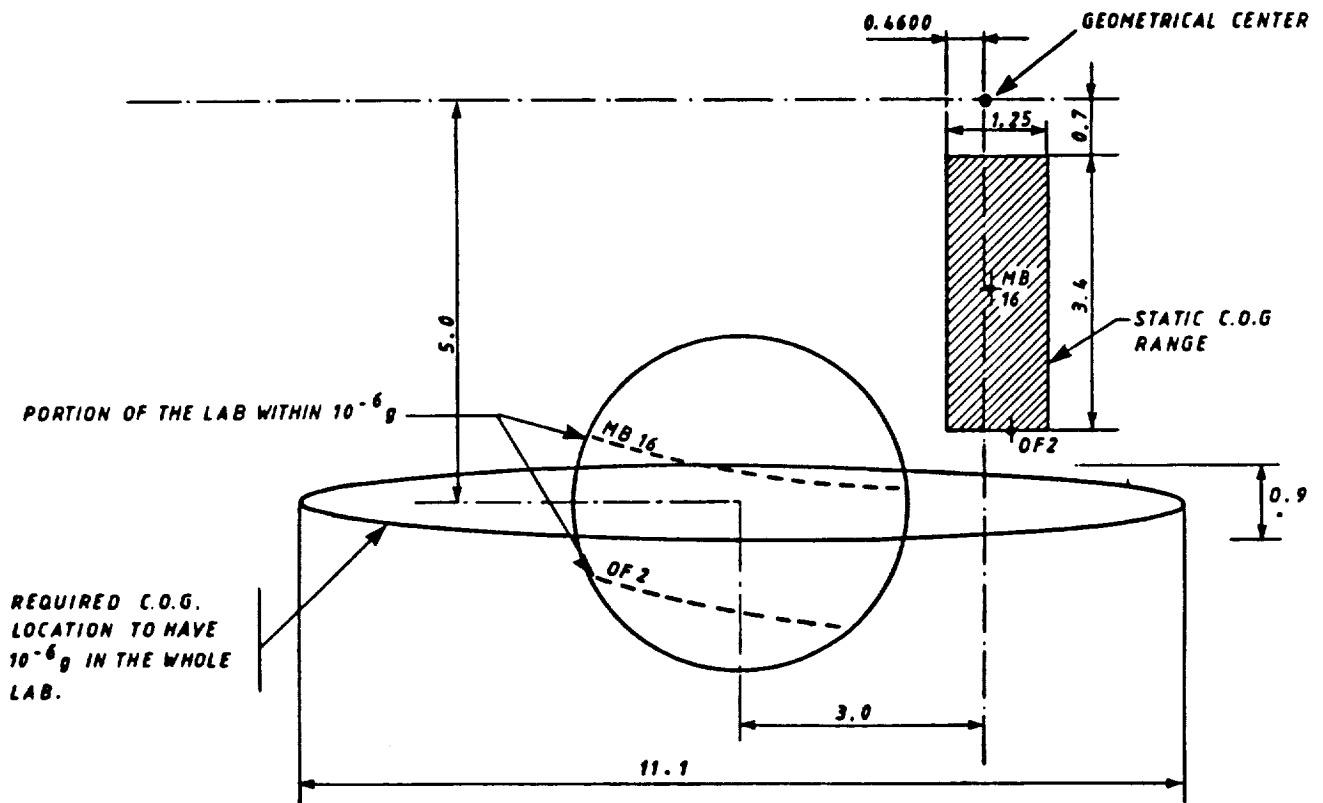


FIG. 2.2-1 GRAVITY GRADIENT 1 MICRO-G ENVELOPES (US LAB)

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The accelerations depend on the Space Station configuration and location examined. Two configurations of the Space Station have been singled out as important:

- 1) Flight OF2 (end of phase-1);
- 2) Flight MB16 (end of phase-2).

Two locations have been thought to be particularly significant:

- a) Center of the U.S. laboratory (which is one of the positions where the disturbances are lower);
- b) End of the European module (which is almost the worst case).

Combining configurations and locations, four cases have been analyzed in terms of acceleration environment. The main results are:

- o mean value of the acceleration along X (which is due to the drag) does not change much between the four cases;
- o mean values of acceleration along Y and Z, which are due to gravity gradient, are distinctly higher in the two MB16 cases;
- o the amplitude of accelerations is markedly higher on the end of the European laboratory (this is due to the effect of attitude motion).

The maximum overall acceleration is something of the order of 1 to 4 micro-g. Other effects could increase the level of steady or quasi static acceleration. Among them there is, for instance, the effect of solar inertial pointing mode of the solar arrays which will cause a periodic torque on the ISS. Another example can be the low frequency component of the random disturbances interesting the Space Station. Obviously the analysis of these effects would require a detailed knowledge of the ISS which was not available.

In synthesis the accelerations due to deterministic causes are near the 1 micro-g level in all the cases considered and well above that on the European and Japanese modules.

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2.3 TETHER CENTER OF GRAVITY CONTROL ANALYSIS

The presence of a tethered system causes, in general, a displacement of the CG along the local vertical. This can be used to reduce the value of the gravity gradient acceleration along Z to an arbitrarily small value in a given point. Moreover with a periodic variation of tether length, periodic accelerations along Z axis can be counteracted. The effect of tethered systems on accelerations along X and Y is, in general, quite small. Tether length variations can be used to damp attitude motion of the Space Station so reducing the g level due to centrifugal forces.

Four tethered system configurations (see Fig.2.3-1) have been selected as basis for our analysis at the end of phase-1 and phase-2 Space Station assembly. The tethered system configurations have been dimensioned assuming that we want to achieve a nominal zero value of gravity gradient acceleration along Z in the center of the U.S. laboratory.

Single tether configuration

The simplest system is made by a single tether pointing downwards. This system has an intrinsically low capability of dealing with dynamic disturbances, but can make null the steady acceleration along Z in a given point. The main features of this configuration at the end of the two assembly phases are shown in Table-2.1. As it can be seen light and relatively small systems are sufficient.

In the phase-1 the resulting length is lower than 2 km and the end mass falls so inside the zone where Space Station full control of every moving object is assumed. This control cannot be easily accomplished in case of tether breakage, unless dedicated hardware is placed on the end mass. Bigger tether length would lead to extremely small end masses complicating so the tether dynamics.

In phase-1 the CG shift due to the tether would reduce the acceleration along z only by few tenths of micro-g, so it does not seem worthwhile to implement such a system for such a small result. A big problem of this configuration is that in phase-1 the Tether Attachment

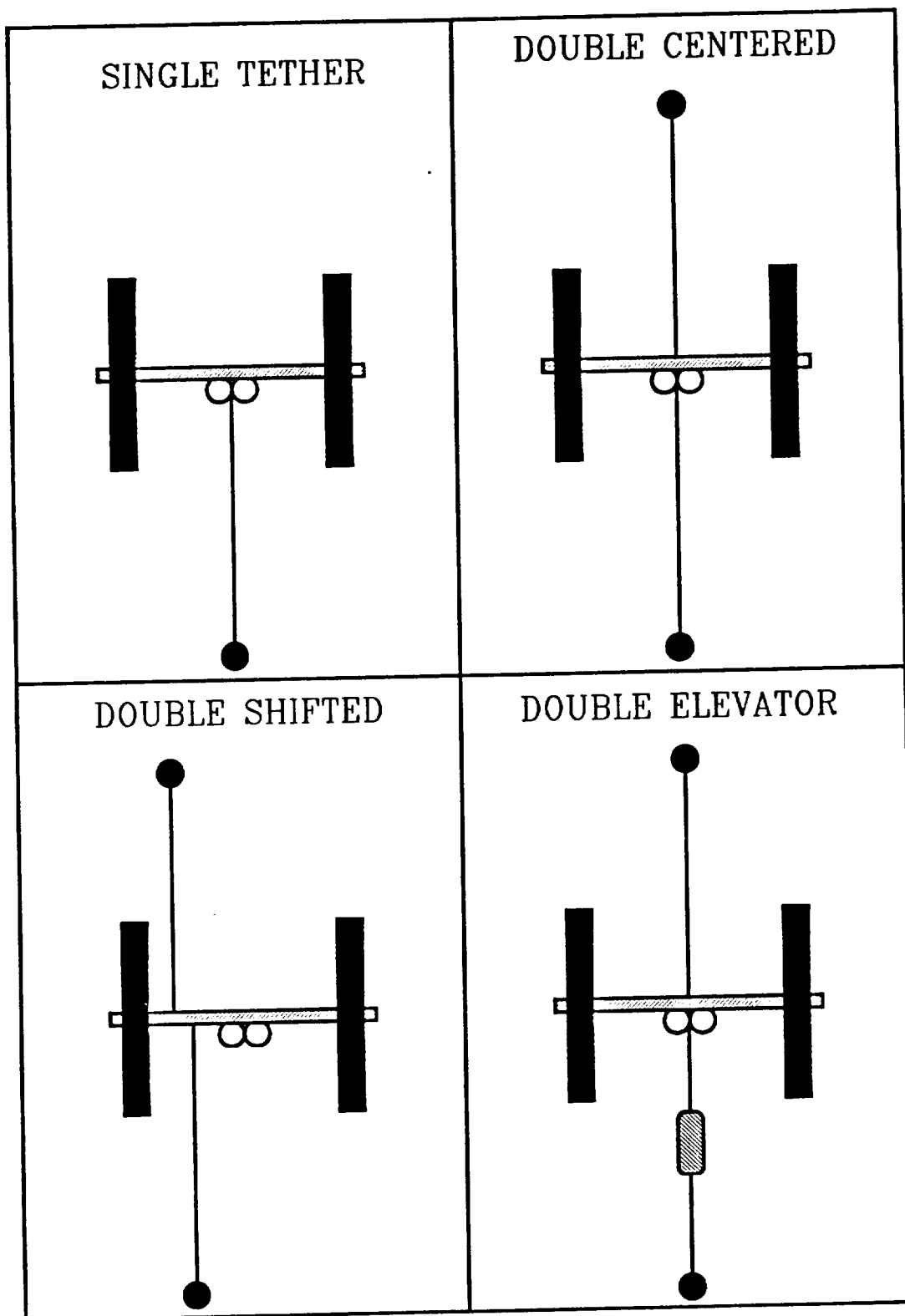


FIG. 2.3-1 TETHERED SYSTEM CONFIGURATIONS

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Point (TAP) has to be placed between the U.S. modules with the consequent clearance problems.

In phase-2 the gravity gradient acceleration along Z is nearly 1 micro-g, so the use of a tethered system is more interesting, furthermore payloads placed on the upper and lower booms can shift sensibly the CG and this can be counteracted easily by changing tether length by a fraction.

Double tether centered configuration

The system is made by two tethers with their TAP's placed along the local vertical through the CG. The tether pointing downward is the mobile system and the fixed one is pointing upward (This is only an assumption. There is no need to have the downward system as the mobile one). The two tethers are not identical as in the dimensioning of the mobile system a big length is an advantage in reducing the tether in-plane librations.

This configuration is the simplest which can counteract both static and dynamic disturbances to a significant degree.

In fact, for the single tether configuration, given that a small static CG shift is sufficient, a relatively short system is required. This implies, given that the ratio between tether length variation and average tether length is constrained to be $\ll 1$, that only small variations of the CG position are achievable with periodic elongations of the tether.

The use of a tether long enough to be able to cope with the assumed dynamic disturbances would cause a large average CG shift. This has to be counteracted by a second tether (fixed) which balances the average effect of the mobile one.

From the numerical results (Table-2.1) it can be seen that the tethered systems characteristics are rather similar in the two cases at the end of phase-1 and phase-2, and the required configuration results in a system that is massive, large and of medium complexity.

The biggest problem of this configuration at the end of phase-1 assembly is that of clearance. In fact, the zone in proximity of the core Space Station is interested by tethers both in downward and upward directions.

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TET. CONFIGURATION	PHASE I SPACE ST.		PHASE II SPACE ST.	
	TOTAL MASS (KG)	TOTAL LENGHT (m)	TOTAL MASS (KG)	TOTAL LENGHT (m)
SINGLE TETHER	149	1660	365	2766
DOUBLE CENTERED TETHER	12080	14224	14196	15227
DOUBLE SHIFTED TETHER	12080	14224	—	—
DOUBLE TETHER + ELEVATOR	9873	10735	11503	11919

TABLE 2.1 TETHER CONFIGURATIONS OVERALL MASS AND LENGTH DATA

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Double tethered shifted configuration

In the intent of overcoming the clearance problem of the double tether configuration a shift of the TAP's along the Y direction is possible. The double tether shifted configuration is almost identical to the centered one (see Table-2.1) except that the TAP's are shifted along the Y axis by approx. 30 m from the middle point of the transverse boom. The average distances of the TAP's from the CG are slightly different as they do not balance each other exactly in order to place the overall CG in the center of the U.S. laboratory.

This configuration is not applicable to phase-2 Space Station where in any case the clearance problem in the immediate proximity of the U.S. modules does not exist being the TAP's on the lower and upper booms.

A problem which affects this configuration is the fact that to avoid undesired torques one TAP has to be moved periodically in phase with tether length variations.

The increase in complexity of the system due to the mobile TAP issue probably outweighs the elimination of the clearance problems.

Elevator configuration

This configuration is made by two fixed centered tethers, on one of which (the downward one) a mobile mass, henceforth called Elevator, is present. This mobile mass accomplishes the same function of the mobile tether but the Elevator configuration is intrinsically more stable than the double tethered centered one. In fact, the end mass on the tether on which the Elevator is placed acts as a stabilizing device for the tether in plane librations.

The study of this system is analytically more complex than that of the other ones as an added degree of freedom is present. To simplify the dimensioning process it has been assumed that the Elevator mass and the end mass of the tether on which the Elevator moves are equal. This is reasonable as the Elevator mass cannot be much greater than the end mass, otherwise the stabilizing effect would be too small; on the other hand an end mass much greater than the Elevator mass probably does not represent an efficient mass distribution.

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The numerical results (see Table-2.1) show that the Elevator configurations, quite similar in the two assembly phases, are noticeably smaller and lighter than the other double tether systems and further optimization appears possible. The same clearance problem found in the double tether centered configuration is present in phase-1, while the Elevator design causes a big increase in system complexity. Again, as in the double tether shifted configuration, an enhancement on certain properties of the system leads to an increase in complexity which questions its worthiness.

Other tether configurations are possible, for instance a shifted Elevator system or an increase to three or four of the tethers number, but these solutions have been judged too complex and full of uncertainties to be investigated at this stage.

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2.4 MAJOR FINDINGS AND RECOMMENDATIONS

The possible benefits achievable by implementation of the various solutions have been judged comparing the capabilities of the systems with the expected disturbances and impacts on the Space Station. The cost has been assessed mainly on the basis of the development risk and expected hardware complexity.

Phase-1 Space Station

In phase-1 the CG appears to be close enough to the U.S. laboratory so that the 1 micro-g level is attained nearly in the whole laboratory. Periodic accelerations of low frequency seem to be within the 1 micro-g level.

This fact and the number of problems due to the position of TAP near the modules (especially clearance problems) lessen the worthiness of a double tether system in phase-1.

The double tether shifted configuration appears too complex (and dangerous in case of tether breakage) to be a sensible solution given the limited results which can be achieved.

The single tether seems to be the only configuration with a limited impact on the Space Station but its usefulness is limited given the already low level of steady acceleration in phase-1.

Phase-2 Space Station

During phase-2 the steady accelerations are higher than 1 micro-g in the most part of the laboratory and could be reduced to 0.5 micro-g using tethered systems. The TAP's are placed on the upper and lower booms reducing greatly the clearance problem and the disturbance transmitted by tethers to the modules.

In general the phase-2 appears a more adequate environment for CG control by tether systems. The use of a simple tethered system is advisable to counteract steady accelerations and will be required if large mass distribution changes (due for instance to large payloads placed on the upper boom) take place.

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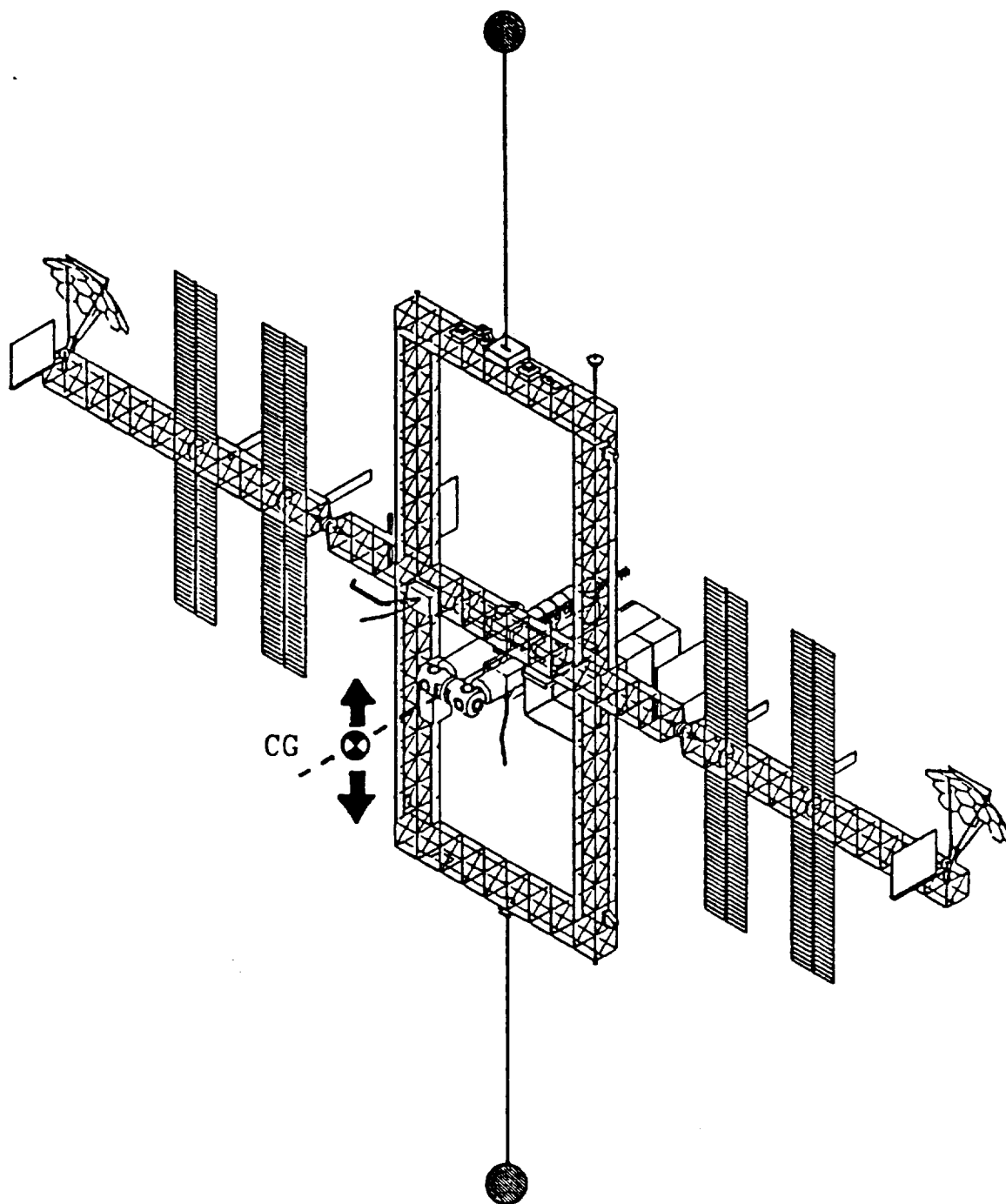


FIG. 2.4-1 CG STATIC CONTROL DURING PHASE-2 SPACE STATION

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The dynamic control of periodic disturbances of the assumed magnitude requires long and heavy systems. The ability of the double tether configurations to deal with significant dynamic disturbances is important, but only if it can be demonstrated that the disturbances are much lower than the assumed ones, more manageable systems can be used, but in that case tether usefulness would cease.

Recommendations

- o During phase-1 the difficulties due to the tether systems are very likely greater than the problems they are required to solve. The cost/benefit figure of tethered systems for CG control is low in phase-1 and further studies are not recommended.
- o During phase-2 Space Station a simple and light tether configuration for static control can lead to a significant improvement on the steady acceleration environment. So, further study of CG static control is recommended for simple systems as that shown in Fig.2.4-1 (Total Mass \approx 2500 Kg, Total Length \approx 8Km).
- o The use of a double tether configuration for CG dynamic control on the phase-2 Space Station makes sense only if a relevant function is found for the end masses. It is possible to think to a multipurpose tethered system which accomplishes the function of CG control among others.
Therefore, further study on the dynamic CG control is opportune but it is so only if pictured in a wider scenario of enhanced Space Station capabilities where CG control is only one of the functions accomplished by tethers.

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SECTION - 3

SUMMARY OF "LOW GRAVITY PROCESSES IDENTIFICATION" TASK

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3.1 INTRODUCTION

Task 2 ("Low gravity processes identification") activities and results are extensively reported in the relevant Task 2 Report TG-RP-AI-001 (iss. 01, 28.02.89).

The focus of this task is on the evaluation of the whole of the experiments performable in a variable gravity environment, and the related compatible/beneficial residual accelerations, both for pure and applied research in the fields of Fluid, Materials and Life Sciences, so as to assess the relevance of a variable g-level laboratory.

The purpose of the mentioned document is twofold:

- to assess which experiments may take advantage of the controlled, variable acceleration levels provided by a Tethered Variable Gravity Laboratory,
- to establish the requirements applicable to such a Laboratory in terms of:
 - magnitude,
 - direction and
 - frequencyof the intentional and residual acceleration levels,

A synthesis of the study performance logics and of the consequent results is given hereinafter.

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3.2 STUDY PERFORMANCE LOGICS

The approach to the activity dealt with in this task moved from the present situation of the experimentation in microgravity ultimately aiming at assessing the worthiness of a variable acceleration laboratory for science and/or production purposes.

Since the Apollo and Skylab era as many as 500 experiments in Material and Life Sciences fields have been performed in absence of gravity, both on board orbiting vehicles and during parabolic trajectories.

Even if the condition of reduced residual acceleration is essential to the experimental purposes, accurate measurements of this condition close to the experimental volume were often neglected, particularly in the past.

In particular, what is missing is the measurement of the acceleration history (g-profile) of the experiments, to be compared with the theoretical predictions of the influence of the residual acceleration vector, not only as a steady field, but also as a function of frequency.

On the other side theoretical analyses, too, are not always available or are sometimes limited to particular cases, hampering the search for widely applicable experiment-theory correlations.

In order to systematically and effectively analyze the aspects related to such a goal within the study frame, an approach based on experiment "building blocks" was selected.

Indeed, the number of basic physical and chemical phenomena involved in micro-g experiments is limited compared to that of the possible experiments and processes themselves.

The starting point of the activity, therefore, was found in the review of the available literature in Fluid Statics and Dynamics, in Thermodynamics and Physical Chemistry, as they face directly the analysis of the fundamentals of such basic phenomena as convection, diffusion, interface stability a.s.o., which provide the key to the understanding of applied science experiments and production oriented tests.

The review was then to be completed in the Materials Science fields, (Crystal Growth, Metal and Alloy

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Solidification, Glasses, ...), by looking for the influence of the previously studied elementary effects on each phase of the considered processes.

Parallel to the mentioned review, mathematical analyses of the relevant physical observable dependance on the g-level were planned being looked after.

In case that possible uncovered areas had been highlighted, a few experts, when appropriate, were to be contacted in order to ascertain whether further unpublished analyses exist.

Preliminary results were - according to the original approach - to be eventually derived in terms of variable g relevance for each experiment class and process or technique by means of the mentioned mathematical analyses and, when appropriate and possible within funding and time constraints, cross-checked and supplemented by experts/scientists advice.

The relevant experiments were finally to be listed and their reduced gravity profiles provided as function of time.

A different approach was chosen for Life Science experiments, whose analysis is usually not pursued by means of mathematical methods due to the intrinsic nature and complexity of the biological phenomena.

G-influence and g-variation relevance to the experiments were to be evaluated directly by literature review and expert consultation via a phenomenological but not mathematical analysis.

As a matter of fact, the above described approach was partly changed during the course of the activity, enhancing the importance of the direct consultation of the scientists versus the theoretical literature elaboration in order to assess variable gravity worthiness for the experimental areas in microgravity.

This adjustment was felt necessary to bypass the obstacles raised by the presence of several uncertainty factors, which were realized during the analysis of the theoretical studies.

Besides, the support coming from the existing theoretical analyses is usually oriented, when available, to the definition of the "optimal" conditions for each kind of experiment (that is: no gravity induced perturbations to

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the phenomena under study). On the contrary, it was often stated by the scientists that "total" gravity effect absence was not the only interesting condition, and sometimes a wide or even a full g-level range availability was declared useful.

In addition, the literature presently available and examined was very poor of suggestions concerning variable gravity uses in microgravitational sciences.

This led ultimately to the conviction that the wider and deeper a campaign of contacts with the involved investigators is, the more defined and complete panorama of possible scientific applications is obtained.

The experimental areas considered in this review were only those where both the reduced gravity aspect is directly essential to the experimental purpose (not merely the orbital position), and the possible applicability to a laboratory environment (close, limited in terms of physical and functional resources - volume, for instance).

Full attention is given, consequently, to Fluids/Materials Science and Life Science disciplines.

Fluids/Materials Science area includes all the experiment classes where fluids and solid materials are involved and where physical and/or chemical phenomena play the key role, without biological phenomena activation (thus, protein crystal growth and biological materials separation techniques are included here).

On the contrary, Life Sciences area includes all the experiment classes where effective biological or biochemical phenomena are present.

In the fluid science domain the following two main areas were scanned:

- fluid mechanics, where mainly fluid statics and dynamics are involved, even in the presence of thermal fields,
- thermodynamics/physical chemistry where, although mechanical effects on the fluid phases are present, the emphasis is on the phenomena related to thermodynamics, with or without the presence of chemical reactions.

As far as applied sciences are considered, most experiments are focused on material production, usually via

solidification from a liquid phase. The following broad classification into three main areas was followed:

- crystal growth, aimed at producing inorganic as well as organic (proteins) materials under crystalline form, mainly from a melt or a liquid solution, sometimes by deposition or transport from a vapor;
- metallurgy, where metallic materials, pure or reinforced with additional components, are looked for; metallic (as well as non metallic) glasses are included in this area;
- bioseparation, which includes all separation processes on biological or pharmaceutical compounds.

In the life science section the following principal areas were examined:

- Animal Physiology, including human physiology and space medicine (crew care and health maintenance)
- Plant Physiology, concerning plant growth in, and adaptation to, the space environment
- Cell Biology and Microbiology, dealing with behavior, activity and genetic modifications of cells and bacteria
- Biotechnology, dealing with the activity of modified cells and microorganisms, for bioproduction purposes.

For each of the mentioned experimental topics the physical or physico-chemical phenomena which bear greater relevance to experiment classes were reviewed with the aim to highlight those phenomena which are influenced by gravity and can motivate investigations in a variable gravity environment.

Gravity influence on experiments, even if not completely clarified, confirmed to be by far much easier to describe in terms of elementary phenomena and much better understood for material science than for biology experiments.

The course of the activity led to realize some basic points related to the concepts of defining and performing experiments in variable gravity.

The scientific interest is predominant in microgravity over the immediate industrial production purposes. Exploitation of microgravity is intended (in Europe) mainly for pure and applied science, the aim being at increasing basic scientific knowledge about several

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basic aspects of the phenomena under study and at providing with guidelines for ground-based material processing.

As testified by the wide set of past mission data, experiments have so far been performed under rigidly prefixed g-level conditions (disturbances included).

Sometimes these are not the best conditions to achieve the experiment purposes and they never allow an assessment of physical processes parametric dependance on the g-level.

For instance, transitions between different prevailing flow conditions or instabilities onset could not be observed.

Another forbidden objective is the provision of further experimental results, at different residual gravity, concerning certain physical effects which are not completely clarified or sufficiently measured or, even, whose presence is uncertain at all.

Past and present literature on the subject contains only very scarce explicit suggestions concerning experiments under variable gravity conditions.

Indeed, only generic statements are found, without any further definition of detailed experiment sequences or even only of specific experiment areas.

Therefore, it was assumed that the primary objective would be the repetition of the experiment runs at different steady g-levels; the g-level would have to be kept constant during each run.

This was deemed adequate for validating existing theories, for extending the existing data to different g-levels, for detecting evidence of significant differences from fixed reference g-level and for clarifying unsolved issues from previous results.

More exotic g-profiles time dependance was considered a less immediate request in the present panorama of interests in microgravity experimentation, except for pure jitter response analysis and for verification of possible hysteresis phenomena (g-cycling).

Indeed, phenomena related to different steady g levels ought to be fully understood (which is not the case to

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date) before more involved and difficult time-dependent g fields can be studied.

The original approach based on the analysis of the theoretical literature to define the g-profiles turned out to be impractical and, even worse, not exhaustive.

Indeed, no detailed process definition was found and, in addition, the search for an "optimum" reduced gravity level for each physical process was recognized not to be sufficient to fully support the definition of the experiments gravity profiles.

As a matter of fact, the search for and the performance at the most appropriate residual gravity level is just one of the possible uses of the Variable Gravity Laboratory.

Performing (many) experiment runs far away from "optimum" condition, that is: far away "no gravity negative influence" condition, turned out to be a possible requirement.

Indeed, the investigators may be looking for evidence of intermediate conditions due to deliberately introduced "gravitational pollution".

Alternatively, they may want to approach by subsequent approximations the unknown, theoretically unpredictable best conditions starting from a trial configuration.

Since it turned out impossible either to deduce such purposes from the theories or to extract them from the available literature, the solution naturally appeared to directly interviewing the scientists, with the support of the knowledge of the available theoretical results, in order to receive direct indication of their interests.

It is important to point out that the best descriptor of the needs of each experimental area - at least for constant g-level experimentation - is not perhaps the usual line in the g vs. time plane (the so-called g-profile).

First of all, physical phenomena are represented by mathematical models and equations where nondimensional numbers or physical variables such as velocities, concentrations, temperatures, geometrical dimensions, thermodynamic and transport properties (density, thermal conductivity, mass diffusivity, viscosity, surface tension and so on), are linked to each other, with a

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number of degrees of freedom.

The approach to the experimental study of certain phenomena, inside any experimental class, under variable gravity conditions will not be limited to the observation of their behavior versus the g-level when all the free parameters are assigned fixed values or time evolutions.

On the contrary, changes in the geometrical configuration, material properties of samples, boundary values and time histories of stimulating fields will be taken into account. This amounts to state that the gravity profile relevant to any phenomena under study is usually affected by each of the mentioned parameters.

In this light, it is evident that a linear g profile versus time can describe only one of the infinite experimental configurations, with defined boundaries and initial conditions and a predefined time evolution.

Therefore, the single g-profile approach does not look suitable to provide a general definition of the needs of an experimental area, where several kinds of substances, different physical and geometrical conditions are met and different time histories are studied.

As a consequence not only one g-level, but a whole of g-levels (a "bandlike" ensemble), is relevant to the same physical situation (e.g. a transition between different motion conditions, an instability onset, any predetermined thermal or solutal field configuration and so forth) just because of a variation in material properties, field variables and geometry.

Further degrees of freedom are added when the examination is extended to regions whose extension is defined by the independent variation (even within predefined limits) of one or more of the involved physical variables.

The linear g-profile, therefore, not being adequate to provide a synthesis of variable gravity experiment requirements, was ultimately substituted by the "g-band", a reasonably simple and straightforward descriptor, defining the minimum and the maximum gravity level enveloping the range where it is worth working into, for each class.

This was also done because so far mathematical theories predicting the g-level dependance of the phenomena are

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not available for all the experimental areas. In addition, geometrical approximations and physical simplifications imply the need for validation of the experimental predictions against the real geometrical and physical complexity.

(In the latter case it should become, therefore, legitimate to reverse the objective "definition of the Variable Gravity Laboratory expected performances by means of microgravity theoretical studies" into "use of Variable Gravity Laboratory to provide experimental data to check uncertain theoretical predictions or to help building not existing ones").

This being the situation, only limited help was to be expected from theories in terms of precise definition of g-bands boundary levels for experiments in variable gravity.

The considerations illustrated so far eventually suggested the adoption of the scientist-in-the-loop working method: a direct screening of the opinion/interest of a selected group of the scientists involved in microgravity activity (mainly in Europe).

As a basis for the discussion, the results of the previously performed review were taken, and support was sought in the available and applicable theoretical assessments.

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3.3 TETHERED VARIABLE GRAVITY PROPOSED EXPERIMENTS AND REQUIREMENTS

Due also to the preliminary character of the mentioned investigation, the results quoted hereafter are not totally conclusive.

They are, however, fairly complete, despite the difficulties inherent in fully describing the complex and interrelated requirements set forth by each experimental area for the research in variable gravity.

Also, microgravity research is in-progress and the whole of its scientific goals is not even completely defined up to now but will need future activity results to become so.

This fact, too, implies that the results of the present investigation are intrinsically "open" to future verification, integration and refinement. They should not have to be used as final and frozen design requirements.

Moreover, a decisive cause is identified in the relative novelty of the "variable gravity" option, a fact which often retains scientists from giving, in a short time, precise indications, compelling their answers within preliminary interest statements, which need further deepening.

However, even if the very potential interest expressed by several investigators suggests that this matter may deserve a further, deeper examination (for instance, by means of an accurate and widely diffused questionnaire) the findings illustrated in the report prove that there is room for a variable gravity tethered laboratory among microgravity experiment tools, to complement fixed g-level research.

Most of the experiment topics which would benefit from a variable gravity environment are found under the heading of material sciences, while it is not clear whether life science experiments can, on the whole, take advantage of a Variable Gravity Laboratory, even if some general interest was raised in the science community by the concept of variable gravity.

A synthesis of the results emerged during the study is given under the form of the following table; when

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possible, the quantitative information relevant to each experimental area is also provided.

For each main experimental area, the possible interest in the variable gravity tethered-based laboratory, its preferred use, the useful gravity level "bands" and the experiment maximum expected durations (order of magnitude) are shown, thus answering the request for "gravity profiles".

In fact, the last two descriptors enable envelopes of possible experiments to be derived in the gravity vs. time plane.

The preliminary character of the displayed information ought to be borne in mind; further and deeper investigation is expected to complete, modify and improve in precision and detail the data and the categories hereafter shown.

In addition, no explicit, clear-cut request for time depending variable gravity has been set forth up to now. This is true both in terms of clear indications of topics (exception made for the problem of the fluid(s)/solid contact angles) and of related gravity versus time profiles. Therefore, this option is not shown in the table.

As a preliminary outcome from the performed assessment of the variable gravity related experiments, a first set of requirements was formulated.

It was also taken into account that the space elevator-based laboratory is likely to be, by its own nature, limited in terms of resources and - at least in the first operative phases - of operational time.

Thence, the assumed utilization philosophy suggested to privilege, as a conceptual baseline, the idea of a single facility carrier, capable to support the repetition of the experiments on different experimental samples or on renewed experimental media at each subsequent different specified gravity level, without intermediate retrievals to the Mother Station.

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EXPERIMENT CLASSES	benefit from variable gravity teth.lab	pre- ferred utili- zation option	useful g-level band (g/g ₀)	experi- ment duration (order of magnitude)
FLUID STATICS & DYNAMICS	Y	S,J	10 ⁻² +10 ⁻⁶	up to hours
THERMODYNAMICS & CRI- TICAL POINT PHENOMENA	Y	S	10 ⁻⁴ +10 ⁻⁶	hours
TRANSPORT PROPERTIES	N	=	=	=
PHYSICAL CHEMISTRY	Y(TBV)	S	TBD	hours(TBV)
COMBUSTION	Y	S	10 ⁻¹ +10 ⁻⁴	min+hours
CRYSTAL GROWTH FROM VAPOR	Y	S	10 ⁻² +10 ⁻⁵	up to weeks
CRYSTAL GROWTH FROM SOLUTION	Y	S,J	10 ⁻² +10 ⁻⁵	days
PROTEIN CRYSTALLIZAT.	N	=	=	=
CRYSTAL GROWTH FROM MELT	Y	S,J	10 ⁻¹ +10 ⁻⁶	hours to days
METALLURGY: METALS, ALLOYS AND COMPOSITES	Y	S,J	10 ⁻¹ +10 ⁻⁶	hours to days
GLASSES	N	=	=	=
SEPARATIVE TECHNIQUES	N	=	=	=
ANIMAL PHYSIOLOGY	N	=	=	=
PLANT PHYSIOLOGY	P	S	10 ⁻⁴ +10 ⁻⁶	days to weeks
CELL BIOLOGY	N/(*)	(*)	N/A	TBD
BIOTECHNOLOGY	P(TBV)	S(?)	TBD	TBD

NOTES: Y = yes; N = no; P = possible; S = steady levels;
J = jitter or vibration response;
TBD = to be defined; TBV = to be verified

(*) : benefits from variable gravity lab are a quite remote
possibility; exo- and radio-biology are possible.

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A single facility configuration should avoid crossed interferences among different experiments running in parallel. At the same time, dedicating the whole resource budget to a single facility should allow a rich and complete set of stimuli actuators, diagnostics means and recording capabilities to be present on board.

This configuration should be suitable to fully exploit the features of this unique experimental tool, permitting to attain unusual experimental conditions with complete environment monitoring available at high cost and for limited operational time.

In order to match the currently known investigators expectations, the following preliminary requirements are proposed, concerning residual acceleration environment features and monitoring:

- full nominal steady residual acceleration level range: 10^{-6} to 10^{-1} g₀;
- within the above mentioned range, availability of discrete nominal steady levels spaced from each other by no more than half an order of magnitude, namely: 10^{-6} , 5×10^{-6} , 10^{-5} , 5×10^{-5} g₀ and so on;
- acceptable deviations from nominal residual acceleration levels (see Fig.3.3-1):
 - nominal levels setting inaccuracy not to exceed $\pm 10\%$ of the nominal level;
 - frequency dependent disturbances modulus not to exceed the following limits, whichever the relative direction of the disturbance be w.r.to the nominal residual acceleration:
 - frequency < 1 Hz: constant, with modulus $\leq 10\%$ of the nominal level
 - $1 \text{ Hz} < \text{frequency} < 100 \text{ Hz}$: matched linear increase with frequency
 - frequency > 100 Hz: matched quadratic increase with frequency

(composition rules for the frequency dependent components TBD, depending on experiments);

- permanence at each specified level: up to 15 days;
- no gravity level continuous variation with time;

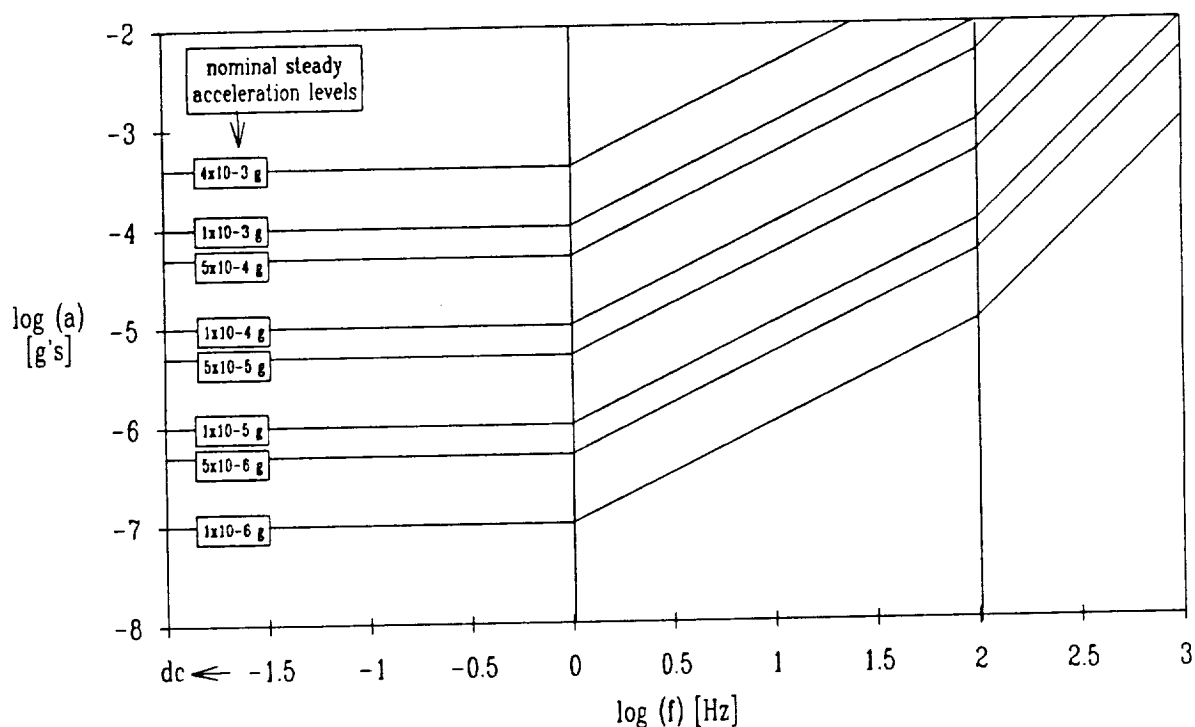


FIG. 3.3-1 MODULUS OF THE ALLOWED FREQUENCY DEPENDANT
DISTURBANCES FOR ANY NOMINAL STEADY LEVEL:
EXPERIMENTAL REQUIREMENT

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- residual acceleration vector direction to remain within a circular cone whose semi-aperture angle is 5 degree (TBV) and whose axis is the experiment significant direction (e.g.: the normal to the plane solidification front); capability to accommodate changes of the significant direction;
 - g-jitter generator provision on the lab. mounted experiment, if jitter analysis required;
 - laboratory triaxial acceleration monitoring as follows:
 - * nominal steady levels ($10^{-6}, \dots, 10^{-1} g_0$) with an accuracy $\leq 10\%$
 - * frequency dependant disturbances up to 10^2 Hz (at least) with an accuracy value less or equal to the maximum dynamic disturbance modulus allowed at any frequency (ref. FIG. 3.3-1)
- (not necessarily by means of the same instrument);
- experiment acceleration monitoring capabilities, in the desired amplitude & frequency ranges, are assumed to be part of the laboratory-mounted experiment itself, as close as possible to the site where the experiment takes place. This in order to discriminate between experiment own and environmental effects. This is a very critical, delicate, and so far underestimated, subject.

Since the above preliminary requirements are related to the experiment-required/recommended gravity profiles, they may undergo modifications and refinements if supplementary investigations are carried out.

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SECTION - 4

TETHERED VARIABLE GRAVITY LABORATORY

4.1 STATEMENT OF THE PROBLEM

The purpose of the Variable Gravity Laboratory (VGL) is to make available to the Space Station users a facility to perform experiments at a controllable and predetermined level of acceleration.

The way of achieving such a result lies in exploiting the gravity gradient acceleration field by means of a tethered system attached to the Space Station.

The gravity gradient acceleration A_g for a point located at a distance z from the CG (Center of Gravity) along the local vertical is:

$$A_g = 3 n^2 z$$

where n is the mean orbital motion and A_g is directed along the local vertical.

Placing the VGL on the tether at a proper distance from the CG (see Fig.4.1-1) it would be possible to cover in a continuous manner a whole range of g levels. Furthermore it is conceptually possible to place the VGL exactly on the CG eliminating completely the gravity gradient effect.

The tether can also reduce the level of acceleration felt by the VGL due to the high frequency mechanical noise generated on the Space Station. So, in line of principle it is possible to reach a better microgravity quality on the VGL than on the Space Station laboratories.

4.1.1 VGL UTILIZATION SCENARIO

The VGL can be seen as a dual capability facility.

The first capability is that of using the VGL as a Variable Gravity Laboratory (in the range 10^{-6} to 10^{-2} g). In this respect the VGL offers a unique capability which cannot be matched by any other facility.

The second capability is the use of the VGL as a microgravity facility where the g quality could be better than the one obtainable on the Space Station retaining an easy access to all Space Station resources.

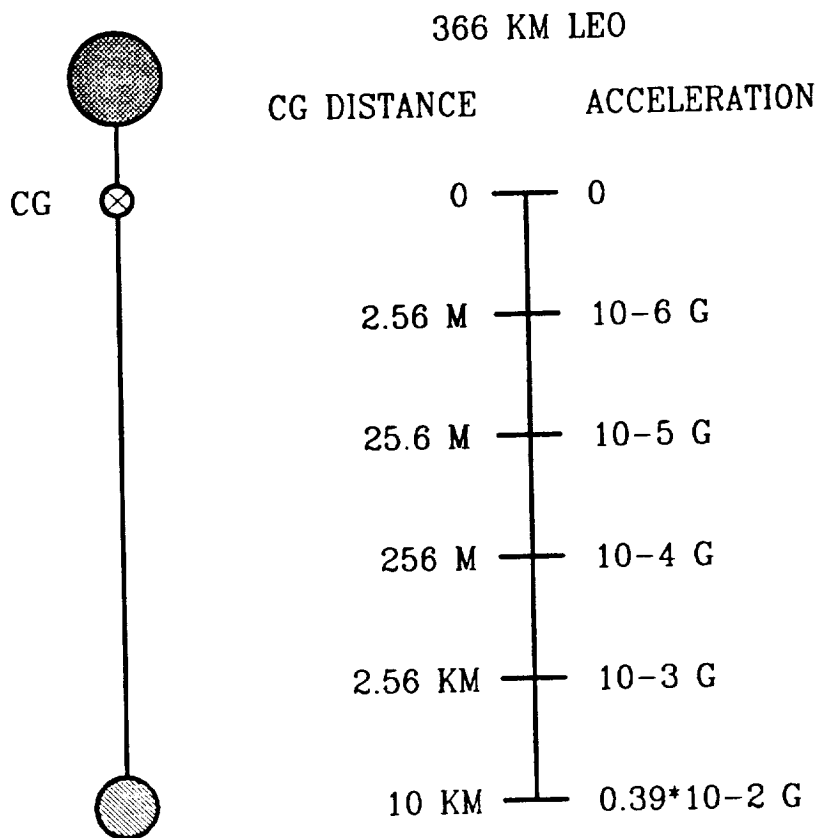


FIG.4.1-1 GRAVITY GRADIENT ACCELERATION VS. CG DISTANCE

So a mixed utilization scenario is foreseeable for the VGL. In Fig.4.1-2 the access time (typical time required to have access) of three classes of potential facilities is cross indexed with the capability of performing microgravity experiments. The "coorbiting" platform, offering a good g quality, requires a long access time as it is not really coorbiting with the Space Station. The Space Station, with easy access to the experiments, suffers from a relatively poor g quality. The VGL could offer the best compromise between the two options.

The VGL is a facility which requires a minimum amount of human intervention being able to perform automatically most of its activities, with the only exception of payload replacement and major tether operations. In our concept the VGL is not a manned system (although human presence can be possible). The VGL is a platform offering to the payloads an adequate set of resources in terms of communication and electrical power supply.

	ACCESS TIME		
	SHORT	MEDIUM	LONG
POOR MICRO-G QUALITY	SPACE STATION		
MEDIUM MICRO-G QUALITY		VARIABLE GRAVITY LAB.	COORBITING PLATFORMS
VARIABLE GRAVITY LEVEL			

FIG. 4.1-2 ACCESS TIME VERSUS CAPABILITY FOR MICRO-G FACILITIES

4.1.2 SCIENTIFIC REQUIREMENTS REVIEW

The discussion of the scientific requirements is reported in Section 3.

Here the requirements having a relevant impact on the VGL concept are summarized. They are:

- g range: from 10^{-6} to 10^{-1} g.
- g profile composed by a number of discrete g levels (one every half decade).
- experiment duration up to 15 days per level.
- 10% error margin on the nominal g value.

The first requirement is the most demanding on the sheer size of the tether. To achieve 10^{-1} g it would be necessary at least a 250 Km long tether. This does not appear a viable option mainly because the estimated tether mass would be of the order of some tens of thousands of kilograms. More reasonable value of the maximum g level obtainable with tethers is of the order of magnitude of 10^{-2} g.

The second point simplifies the design of the VGL and allows a number of possibilities for what regards the VGL configuration.

The experiment duration does not constrain the VGL itself but it is important as it establishes a minimum duration of the period during which VGL is in use.

The last point is the more demanding from the point of view of the dynamic performances. In fact, given that the requirements on the Space Station assure an acceleration level of 10^{-5} g (at all frequencies), this means that an attenuation factor between 10 and 100 for disturbances coming from the Station is required on the VGL to comply with the requirement at 10^{-6} g.

4.2 CONFIGURATIONS EVALUATION

A wide range of VGL configurations is possible many of which need at least some attention. It was thought opportune to investigate the configurations at various levels of system design and to proceed progressively narrowing the scope of the investigation in order to avoid unnecessary analysis effort.

The levels at which the investigation has been performed are:

Space Station level

A first analysis has been focused at the most general level of system configuration concerning aspects as:

- VGL as a permanent or temporary facility.
- phase-1 and phase-2 Space Station.
- number and position of tethers.

Tethered system level

Having chosen a preliminary tether system/Space Station configuration, the tethered system has been defined regarding mainly the VGL position on the tether and the way to change the VGL distance from the CG.

VGL analysis

At this point a preliminary sizing of the VGL has been performed defining tether size and material, VGL and ballast mass. Furthermore the basis for operations involving the VGL has been tentatively devised.

Obviously all these analyses have a certain amount of overlapping and relationship among them which has been considered, but the basic approach was a top down one. The design decision logical flow is shown in Fig.4.2-1.

4.2.1 SPACE STATION LEVEL CONFIGURATION CHOICE

Looking at all the possible configurations three basic design decisions have to be made:

a) Permanent versus temporary facility

The problem here is to decide whereas the VGL has to be thought as something which is a permanent facility or if it is required that the VGL is operated only for a certain time fraction (this can be required to reduce

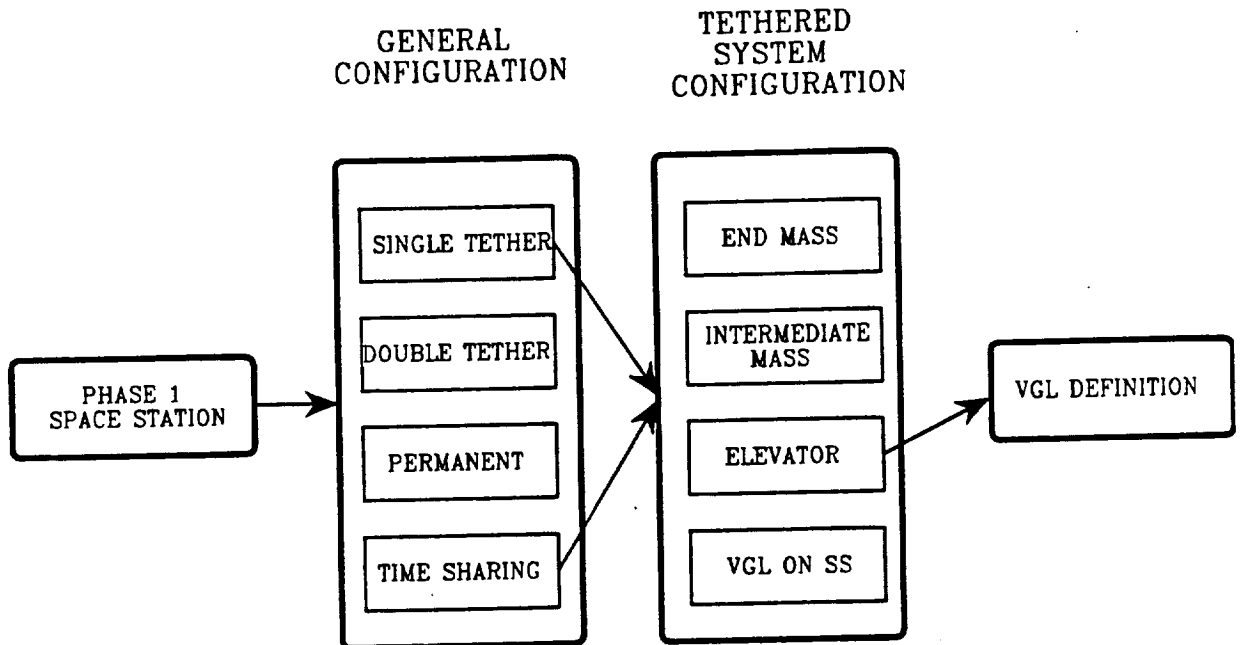


FIG. 4.2-1 VGL CONFIGURATION SELECTION LOGICAL FLOW

the amount of time during which the VGL presence impacts on the overall Space Station system). Two problems can cause some concerns:

Operational constraints.

A permanently deployed tethered system generates a number of constraints on EVA and rendezvous operations held in the proximity of the tether; large attitude maneuvers and reboosting call for an increased attention with tether systems. On the other hand a temporary system would need more tether retrieval and deployment operations.

G level on the Space Station.

The g level on the Space Station is influenced by the presence of tethered systems (as they can shift the CG of the Space Station). If a single tether system is used the Space Station g level is worsened at least proportionally to the maximum required g level on the VGL system. Using a two tether system (one tether deployed upward and the other downward) it is possible to reduce the g level on the Space Station for large values of the gravity gradient acceleration on the VGL. For small

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values of the g level on VGL the limiting factor for the Space Station environment is the minimum distance required to insulate satisfactorily the VGL from Space Station mechanical noise.

b) Phase-1 versus Phase-2 Space Station

During phase-1 the operational problems involved due to the presence of tether are more important due to the necessity of placing the Tether Attachment Point (TAP) near the laboratories. This can be avoided using a double tether shifted system (with the TAP shifted along the direction perpendicular to the orbital plane) but the system in this case would end up as a quite complex one (the TAP should be moved when the tension is changing to keep null the torque around the center of mass). Phase-2 Space Station is more apt to the use of tethered systems given that the TAP can be placed on the upper or lower booms but the time frame of its in orbit placement is much more undefined respect to phase-1 Space Station.

c) Single versus double tether system

The single tether system has the advantage of being simple both in implementation and in operation but has some drawbacks:

- TAP is required to be on the local vertical through the CG which in phase-1 can cause operational problems.
- Worsening of the g quality on the Space Station.

Double tether systems can be used to reduce the time during which the $10 \mu g$ requirement is violated, but this would require a second tethered system which has the same size (in terms of mass and tether length) of the one carrying the VGL. Furthermore a much more sophisticated system would be required to control simultaneously both tethered systems.

Multiple tether systems do not appear to offer any advantage over simpler systems so they have not been analyzed.

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4.2.1.1 Choice rationale

Here the purpose is to analyze the possibility of early implementation of the VGL and so the phase-1 Space Station has been selected as baseline. In this scenario the VGL has to be seen as an added capability of the Space Station and has to be utilized only when required, so a time sharing VGL is adequate.

Seen as a microgravity payload, used only occasionally and for relatively short duration, the VGL would not be disruptive of the microgravity experiments being "the" microgravity experiment at that time. To keep the impacts on the Space Station limited, the single tether system is preferred and this reinforces the decision of using a time sharing VGL.

Looking further in time at the phase-2 Space Station it is possible to think to a VGL which has demonstrated its usefulness and it is utilized as a permanent facility. This in turn will require a double tether system to reduce impacts on the Space Station (in particular to reduce the CG shift when high g levels are required on the VGL). In this scenario the ballast masses will be used in a more extensive mode (for instance as platforms for Earth and space observation).

So, the following analysis concentrates on the phase-1, time sharing, single tether system but that is not to say we discard the phase-2 Space Station scenario which will be possibly analyzed further in time.

4.2.2 TETHERED SYSTEM LEVEL CONFIGURATION CHOICE

A variety of possible configurations for the VGL system have been analyzed in order to assess the best way to control the g level varying the VGL distance from the CG.

The investigated VGL system concepts are shown in Fig.4.2-2 and are:

- 1) VGL as end mass of the tethered system.
- 2) VGL locked to an intermediate point of tether.
- 3) VGL as an Elevator able to move along the tether.
- 4) VGL on the Space Station.

End mass

The end mass of the tethered system can be used as a VGL. In this case it would be impossible to achieve low values of g in the VGL if it is assumed that a not negligible tether length is required to attenuate the mechanical noise coming from the Space Station. As we have assumed that a 150 m tether length is required for this purpose, the minimum g level would be of the order of 10^{-4} g and this configuration becomes less than promising.

Intermediate mass

The VGL could be a mass rigidly connected to an intermediate point of the tether. In this case a ballast mass would be needed at the end of the tether to stabilize the system against in plane lateral oscillations. This solution is quite simple conceptually and would simplify greatly the VGL design if the portion of tether between the Space Station and the VGL can transmit electrical current (and possibly data through an optical fiber link) reducing so the amount of on board stored energy. Two problems are evident at this stage:

- a) When the tether is retrieved up to the VGL location a certain tether length is still deployed, and the problem arises of how to retrieve the ballast mass. Two ways are possible to overcome this problem:

- o Detach the VGL from tether and continue tether retrieval (meaning that the tether is passing through or around the VGL).

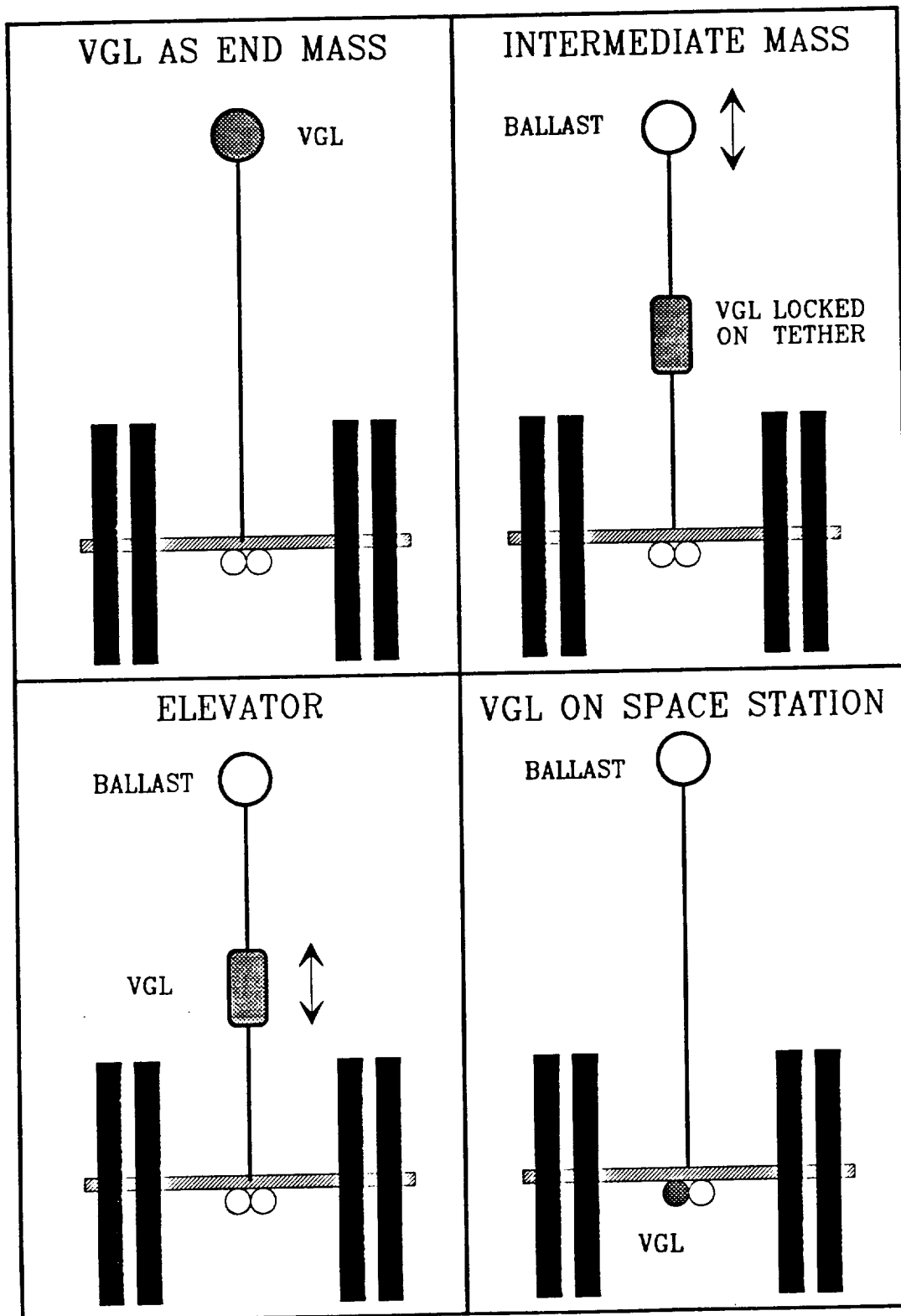


FIG. 4.2-2 VGL CONCEPTUAL CONFIGURATIONS

o Use a reel inside the VGL to retrieve the last portion of tether (meaning that there are effectively two distinct tethers).

- b) Since the distance between VGL and ballast mass is constant during a mission, an unavoidable inefficiency on the use of tether length is implied. This point is discussed more thoroughly in the Elevator paragraph. Here it is sufficient to say that the g level on the ballast mass is always greater than that on the VGL so the tether capability is not completely exploited.

Elevator

The Elevator concept envisages a VGL that is able to move along a tether, the length of which is held constant. For a given VGL mass and minimum distance from the Space Station, the dimension of the system can be quickly found.

Let us suppose for now that the tether is massless.

Assuming the following notations:

M_S = station mass

M_b = ballast mass

M_e = Elevator mass

X_S = Space Station distance from CG when the Elevator is on the CG

X_b = ballast mass distance from CG when the Elevator is on the CG

L_S = Space Station distance from CG when the Elevator is the farthest possible from CG

L_b = ballast distance from CG when the Elevator is the farthest possible from CG

L_e = maximum possible Elevator distance from CG

Then when the Elevator is on the CG we have:

$$M_S X_S = M_b X_b \quad 1)$$

And when the Elevator is the farthest possible from CG:

$$L_b \approx L_e$$

$$M_S L_S = (M_b + M_e) L_e$$

The maximum level of acceleration obtainable is then:

$$acc_{max} = 3 n^2 L_e$$

If the tether length is constant, we can assume:

$$X_s + X_b = L_s + L_e = L_t = \text{total tether length}$$

And given the high Space Station mass:

$$L_t \approx L_e \approx X_b$$

For the intermediate mass configuration the equation 1) holds too if we assume the same mass for the ballast.

In order to have the same maximum level of acceleration of the Elevator case it has to be (approximately):

$$L_b \approx L_e + X_b \approx 2 L_e$$

$$M_s L_s = (2 M_b + M_e) L_e$$

So with the same requirements and the same VGL and ballast masses we found that, using the intermediate mass configuration the maximum tether length required is twice that of the Elevator configuration.

VGL on the Space Station

Using a tethered mass it is possible to achieve a degree of g level variation inside the Space Station. Given the Space Station mass the g level range is quite limited. In fact, with a ballast of 10 thousands of Kg and a 25 Km tether, the g level on the Space Station would be a mere $5 \cdot 10^{-4}$ g. Furthermore the requirements emitted for the Space Station state the presence of a 10^{-5} g noise level on board the Station itself. This implies that an uncertainty of 20 % is present even for the maximum achievable g level. So this solution does not seem worthwhile to be further investigated.

A summary of the points previously discussed is reported in Table-4.1.

From that it can be seen that only the intermediate mass and Elevator configurations can satisfy the basic requirements.

The choice between these two configurations has been performed mainly on the ground of the exceedingly big tether length of the intermediate mass configuration, which is a serious drawback both for the required mass and for the required duration and complexity of operations.

The Elevator seems simple enough to be implemented and complex enough to be flexible. Three are the main open problems :

	END MASS	INTERMEDIATE MASS	ELEVATOR	VGL ON SPACE STATION
LOW G	NO	YES	YES	YES
HIGH G	YES	YES	YES	NO
LOW NOISE	YES	YES	YES	NO
SYSTEM COMPLEXITY	LOW	AVERAGE	AVERAGE TO HIGH	LOW
TETHER LENGTH	AVERAGE	HIGH	AVERAGE	HIGH

TABLE 4.1 VGL CONFIGURATIONS MAIN FEATURES

- a) Motion of the Elevator. The problem lies in defining how to accomplish a reliable and accurate motion of the Elevator driven by a motor located on the VGL and using the tether as a "rail".
- b) In the same field of the problem above mentioned there is the question of how to attach and detach the Elevator from the tether.
- c) Given that the Elevator is mobile w.r.to the tether, it is not easily possible to use the tether itself to carry the electrical current needed by the VGL. So either the VGL is able to store enough on-board energy to perform its mission or a second cable (possibly slack) is used to transmit the electrical current.

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4.2.3 PRELIMINARY VGL SYSTEM DEFINITION

4.2.3.1 VGL System Sizing

The VGL system is basically dimensioned by three parameters:

- Elevator mass
- Minimum distance between Elevator and Space Station
- Maximum required level of g

The preliminary Elevator mass is assumed to be 2000 Kg. The minimum distance between Elevator and Space Station is determined by the necessity of insulating the Elevator by the disturbances present on the Space Station. The correct value of this minimum length (X_S) depends on many variables as tether material properties, tether tension, ballast mass, characteristic disturbances, but a preliminary value of 140 m appears a sensible choice. This value should be kept as small as possible to reduce the size of the counterweight mass and overall tether length (This assumption is validated by result of simulations).

The VGL sizing can proceed assuming a constant tether length L and with the equations:

$$(M_S + \mu/2 X_S) X_S = (M_b + \mu/2 X_b) X_b$$

$$(M_S + \mu/2 L_S) L_S = (M_b + \mu/2 L_b) L_b + M_e L_e$$

Where μ is the tether linear density and the other symbols are defined in section 4.2.2.

The tether linear density is a function of the material capability to stand damage due to meteoritic impact and of the tether length. In our case material properties equivalent to those of Kevlar have been used (Kevlar is interesting especially for its low thermal expansion coefficient). A 95 % probability of survival after one year of exposure has been assumed.

A sweep has been made through the value of L_e (which is the maximum distance of the Elevator from CG). The total system mass depends on two parameters:

- ballast mass which decreases with tether length (for a given X_g)
- tether mass which increases more than linearly with length.

A minimum total mass has been found for a total length of 10500 m leading to a maximum value of $4 \cdot 10^{-3}$ g for the steady acceleration level on board of VGL. As this appears a reasonable value it has been selected as a preliminary baseline. The resulting tether diameter is 0.01 m and the ballast mass is 2200 Kg.

Summarizing, the preliminary sizing of the VGL has been assumed to be:

Station mass	=	204500 Kg
Elevator mass	=	2000 Kg
Ballast mass	=	2200 Kg
Tether material	=	Kevlar
Kevlar density	=	1440 Kg/m ³
Young module	=	62 GPa
Tether length	=	10500 m
Tether diameter	=	0.01 m
Minimum Elevator distance from Space Station	=	140 m
Maximum acceleration level on Elevator	=	$4 \cdot 10^{-3}$ g

4.2.3.2 Constant Versus Variable Tether Length

To change the acceleration level on board of the VGL the Elevator is moved using the tether as a "rail". In Table-4.2 the positions of the Elevator and Space Station w.r.to the CG and the values of gravity gradient acceleration are reported. It can be seen that when the tether is deployed the requirement of 10^{-5} g on Space Station is violated by an order of magnitude. The possibility of changing the tether length during a mission has been then investigated.

Two can be the purposes of such a maneuver:

- to reduce the time period during which the $10 \mu\text{g}$ acceleration requirement is violated on Space Station.
- to reduce risk of tether damage due to meteoritic impact.

Elev. Acc. (Log g)	L _e (M)	X _s (M)	Station Acc. (Log g)
-6	3	136	-4.27
-5.5	8	136	-4.27
-5	25	136	-4.27
-4.5	79	136	-4.27
-4	251	138	-4.26
-3.5	795	143	-4.24
-3	2514	160	-4.2
-2.5	7949	212	-4.07
-2.379	10507	237	-4.03

TABLE 4.2

On the other hand to change the tether length is a complex operation which should not be performed if it is not really required.

The analytical results are reported in Fig.4.2-3. It can be seen that only for a short range of g level on the Elevator (near to 10^{-4} g) the Space Station requirement can be met, and the deployed tether length is reduced in a significant manner only in the range 10^{-3} to 10^{-4} g.

At a first evaluation the drawbacks of changing the tether length appear bigger than the possible advantages so the baseline choice of keeping constant the tether length is sound.

The order with which the Elevator will sweep the g levels will be defined by the experimenter but in line of principle it would be better to proceed from low to high g levels.

This implies that the Elevator progressively increases its distance from the Space Station and the stabilizing effect so generated will help in reducing the settling time of the in plane lateral oscillation caused by the Elevator motion.

The baseline mission duration is thought to be of the order of one month. This was decided for three reasons:

- the overall duration seems able to satisfy most of the experiments mission profiles (in terms of the product of experiment duration at each level for the number of levels used) ;

- to keep under reasonable limit the time during which the 10 μg requirement on Space Station is violated;
- to avoid unreasonable requests on the Elevator on-board resources.

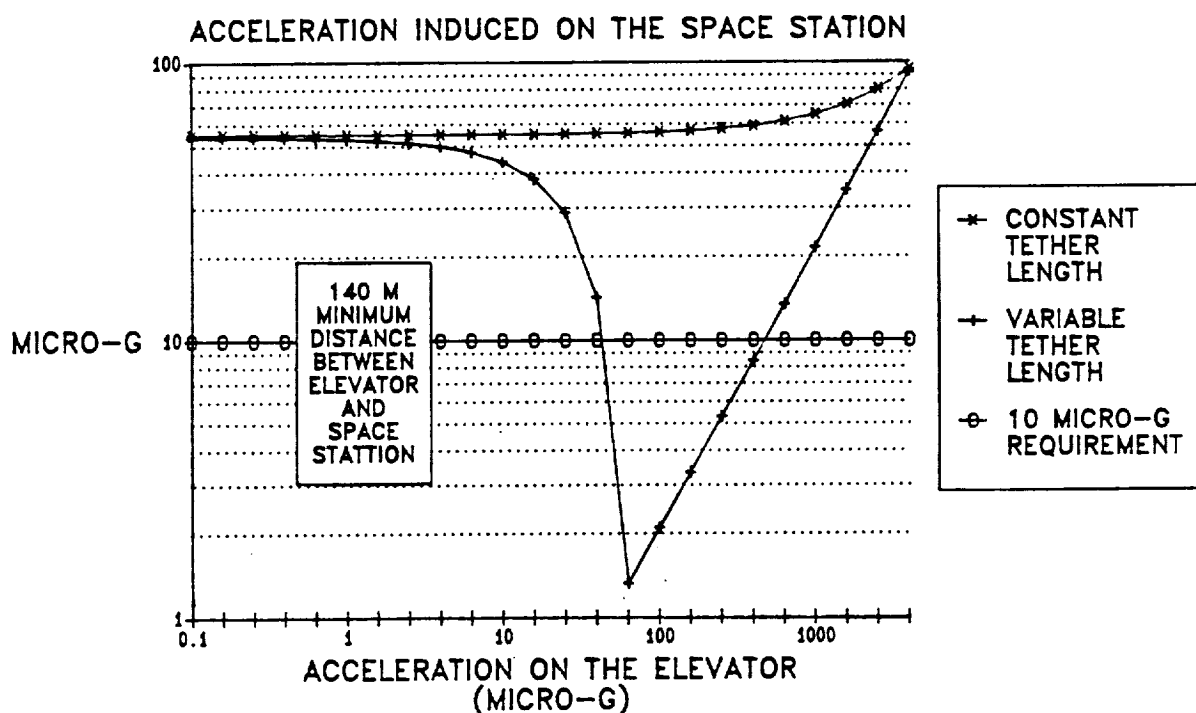


FIG. 4.2-3 ACCELERATION LEVEL ON SPACE STATION FOR CONSTANT AND VARIABLE LENGTH OF TETHER

4.3 ELEVATOR CONCEPTUAL CONFIGURATION

4.3.1 ELEVATOR HOOKING ON THE TETHER

One of the most problematic and unique areas of the overall Elevator VGL concept is the area regarding the hooking of the Elevator on the tether. In this section the impact of various hooking concepts on the Elevator configuration and on tether operations (deployment and retrieval) is examined. Four basic options are analyzed at a conceptual level.

In general for the purpose of this discussion it is assumed that the Elevator is attached to the tether in two points in the "top" and "bottom" locations (this assumption does not impact in most of the analysis).

4.3.1.1 "Slot" Configuration

A natural idea for interfacing the Elevator with the tether is to use a slot on the Elevator through which the tether is introduced (see Fig.4.3-1). After Elevator hooking on the tether the slot could be closed to increase Elevator structural stiffness.

In this scenario the ballast is already extended at its operational location. The Elevator is moved near the tether by means of a suitable RMS-like system or using some kind of translation guide.

The advantage of this solution is that it is possible to attach and detach the Elevator from the tether without need of tether operations (deployment/retrieval).

In our case, the tether is deployed only for a limited amount of time, and in general the Elevator attachment/detachment is immediately preceded/followed by tether operations.

The main topics of this solution are quite clear:

- a) Impact on the Elevator configuration which needs to be cut along a plane throughout its height (dimension along the tether direction).
- b) Precise maneuver required to hook the Elevator on the tether (accurate positioning and motion are required to avoid damage to the tether).

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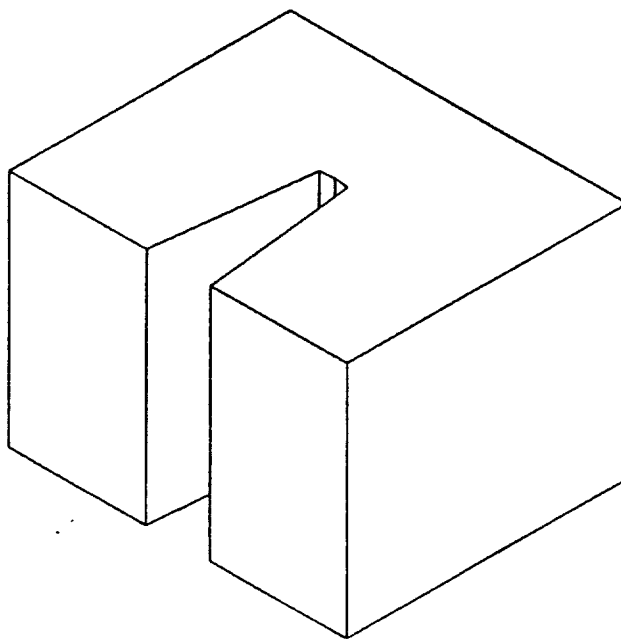


FIG. 4.3-1 SLOT CONFIGURATION

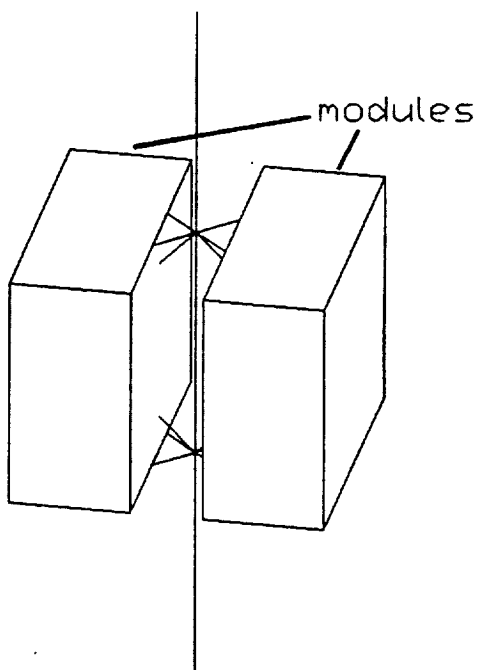


FIG. 4.3-2 TWO MODULES CONFIGURATION

A solution which is conceptually similar to the slot solution is the two modules solution (see Fig.4.3-2). In this case the linkage between the two sides of the slot is kept to a minimum. The two modules could be used for different functions ,i.e., one of them supporting all the service equipments and the other carrying the payloads.

Although attractive in line of principle, in practice there are so many functions (thermal control, OBDH, EPDS) which have to be shared between the two modules. If ,on the other hand, the modules are required to accomplish the same functions we would end up with a duplication of many equipments. Moreover the operational sequence of events presents some problems:

- a) If we imagine to connect together the two modules before tether hooking, the sequence is substantially similar to the basic operational sequence for the generic slot configuration with an added task (connect the two modules).
- b) If the first module and the hooking system are mounted on the tether and then the other one is connected, the problem is somewhat different. The request for complex and critical connections between the two modules in a limited working space relies heavily on the hypothesis of direct human intervention (possibly EVA), which is one of the most precious and scarce resources on the Space Station.

4.3.1.2 Shaped Tether Configuration

It is conceivable that instead of having a straight tether going through the Elevator, we use a tether going around the Elevator keeping the Elevator center of mass along the projection of the tether line (Fig.4.3-3).

This greatly simplifies the Elevator design but worsens the situation for the tether. In particular the hooking on the tether, if in tension, is much more complex and of doubtful feasibility. Moreover it is easy to see that with a tether of respectable diameter as our one (10 mm diameter) we can likely cause large stress in the tether fabric.

If the tether is not in tension this means that the tether is not deployed at the moment of tether attachment and in this case other solutions (that are analyzed in the following pages) appear more promising.

Another problem which is unavoidable is the fact that during Elevator motion a transversal displacement "wave" is travelling along the tether superimposed to the one caused by the Coriolis force on the tether.

4.3.1.3 Unbalanced Configuration

It has been always assumed in the previous discussion that the Elevator center of mass must lie on the projection of the tether line. If we remove this constraint the Elevator can be simply hooked on one side to the tether (Fig.4.3-4). This again leads to a great simplification of the Elevator design.

In turn we have a torque around the rotation center which has two main consequences:

- a) There are displacements of the two tether portions (after and before Elevator) and of the Elevator itself such that an equilibrium position is achieved. If we neglect the stiffness of the tether, the Elevator and the tether portion along the Elevator position themselves in such a way to not induce any resultant moment. The angle that the longitudinal axis makes with the local vertical depends on the Elevator geometry and on its position along the tether. For increasing Elevator distance from Space Station the gravity gradient force acting on the Elevator increases and hence a larger equilibrium angle results.

Moreover this angle changes quite quickly with the distance from Space Station, adding a further dynamic effect to the already complex tether dynamics.

- b) The tether (which is a beam) undergoes a substantial stress due to the gravity torque.

The simplification in Elevator configuration is relative; in fact the exigency of keeping the Elevator CG as close as possible to one of its sides can lead to important disadvantages as putting the batteries (which are probably the most massive elements) near the tether, further reducing the amount of space which can be used for microgravity experiments (location near the tether is the best for low disturbances).

The Elevator handling during hooking can still be faced by problems even if it is simplified with reference to what it is encountered with the "slot" configuration.

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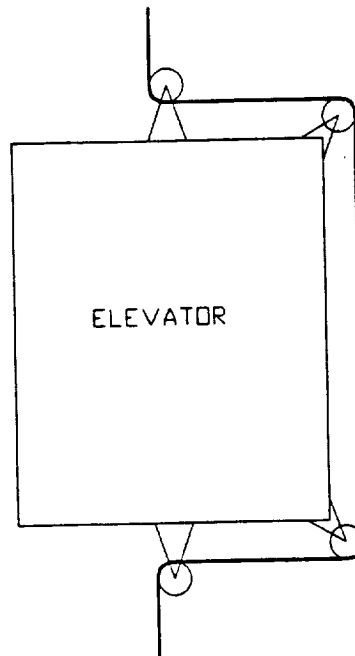


FIG. 4.3-3 SHAPED TETHER CONFIGURATION

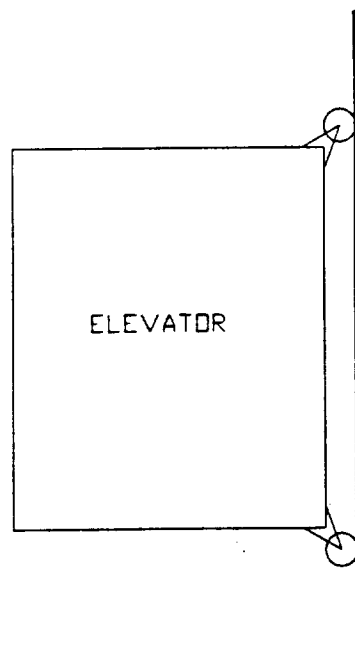


FIG. 4.3-4 UNBALANCED CONFIGURATION

4.3.1.4 Hole Configuration

The simplest Elevator configuration which can house a tether is one with an hole running throughout its longitudinal dimension. In this way we achieve the lowest impact on the Elevator which has merely to keep a cleared zone of some centimeters around the longitudinal axis through its CG (see Fig.4.3-5). No structural weak points or additional constraints on subsystem location are present. On the other hand it is required that the tether is completely retrieved to attach/detach the Elevator from it. In a permanent tether scenario this would be probably an unacceptable requirement, but in our case this is something which is not only foreseen, but necessary (both for tether survival and for reducing impact on Space Station microgravity experiments). The tether is introduced within the Elevator hole using a rigid guide slightly longer than the Elevator longitudinal dimension. With the guide protruding from the Elevator we can then attach the ballast to the end of this guide.

Among the various advantages of this configuration, we can cite:

- a) Reduced number of mechanisms.
- b) Higher structural stiffness especially around the tether axis.
- c) Better thermal coupling within the Elevator.
- d) For a given Elevator size the room left empty for tether operation is kept to a minimum.

The operation sequences of events for this configuration and for the "detachable" one are reported and commented in the following section.

4.3.2 OPERATIONS ANALYSIS

Analysis and identification of tether operations are fundamental issues in the evaluation of the relative merit of the possible Elevator configurations. What follows it is a notional sequence of events which take place during normal and emergency (system components malfunctioning) situations. The two configurations compared are the "hole" one and a generic "detachable"

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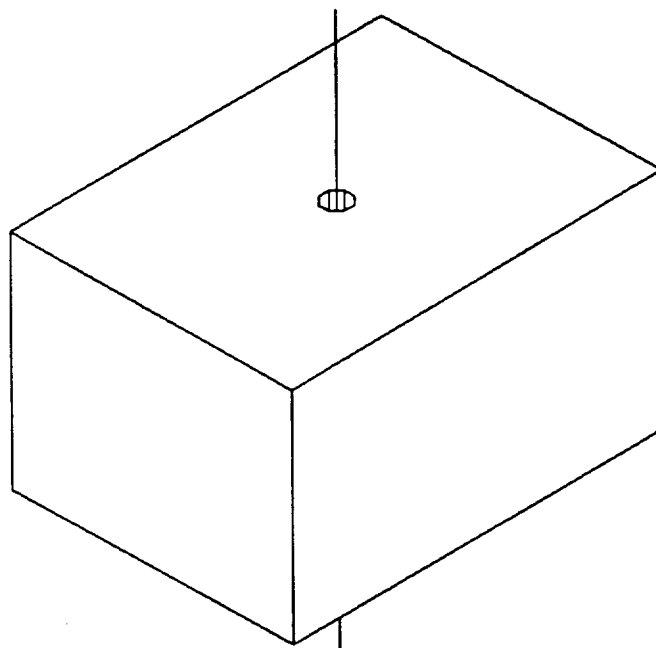


FIG. 4.3-5 HOLE CONFIGURATION

configuration which does not require tether operation to be attached/detached from tether. It must be remembered that minor payload/service maintenance operations can be made with the tether still deployed, but for most of the times, a VGL mission involves the complete sequence of events.

4.3.2.1 Nominal Operations

Deployment of a "detachable" Elevator

- 1) Ballast deployment.
The tether is payed out until the ballast is deployed to the nominal distance from the Space Station.
- 2) Elevator hooking.
The Elevator is hooked on the tether by RMS or proper translation guide.
- 3) Elevator deployment.
The Elevator is moved from the Space Station to the nominal position to start the experimental activities.

Deployment of a "hole" Elevator

- 1) Tether insertion through the Elevator.
A rigid guide goes through the Elevator hole.
- 2) Ballast attachment.
The ballast is attached immediately near the "hole" Elevator possibly on the rigid guide itself. In this way the two bodies (Elevator and ballast) behave as a single one avoiding dynamic instability problems.
- 3) Elevator and ballast deployment.
The Elevator and the ballast (rigidly connected) are deployed to the nominal tether length.
This is necessary to avoid the tether to be payed out passing through the Elevator if it is kept docked to the Space Station.
In fact, if the tether is payed out passing through the Elevator without any contact with it, there is the risk that tether motion causes the tether to rub against the walls of the hole.

If there is contact between the tether and the Elevator mechanisms, there is an added uncertainty in the physical variables (length, speed and tension)

which have to be controlled during tether deployment. Another issue is the fact that the maximum deployment rate can be larger than the maximum speed of the Elevator actuators. In this case there would be the risk of overloading the Elevator actuators.

- 4) Elevator deployment
The Elevator is moved from its position near the ballast to the position to start experiments.

Notice that the "detachable" Elevator can perform the same operational sequence that the "hole" Elevator can do. The reverse is not true.

The operation sequences for retrieval are almost the same, executed in reverse order:

Retrieval of a "detachable" Elevator

- 1) Elevator retrieval.
The Elevator is moved near the Station at its docking point.
- 2) Elevator unhooking.
- 3) Ballast retrieval.

Retrieval of a "hole" Elevator

- 1) Elevator-ballast docking.
The Elevator is moved and docked to the ballast for the same reasons which apply to deployment.
- 2) Elevator-ballast retrieval.
- 3) Ballast detachment.
- 4) Elevator detachment.

In general it can be said that the nominal operations sequence for the "hole" Elevator is more cumbersome than that for the detachable Elevator.

4.3.2.2 Emergency Operations

It is assumed that Elevator salvage is mandatory. Let us start with the Elevator far from the Station on the tether. There are two possible kinds of emergency that can be of interest:

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Tether reel jammed

Depending on the presence of solar arrays and on the bare minimum power consumption, the Elevator may impose a time constraint to its permanence on the tether. So there can be the need to retrieve the Elevator without waiting for the reel to be repaired or substituted.

"detachable" Elevator operation sequence

- 1) Move Elevator near the Station.
- 2) Detach Elevator.
- 3) Repair tether reel.
In the worst possible case (e.g. jamming of the tether reel bearings) the tether can be cut.

"hole" Elevator operation sequence

- 1) Move Elevator near the Station.
- 2) Perform maintenance operations.
Take away payloads, replace batteries (if needed).
- 3) Repair tether reel.
The same considerations made for the detachable Elevator are valid. There is not in any case the risk of loss of the Elevator as the tether can be cut beyond the Elevator itself.

Elevator jamming

The Elevator actuators can be jammed or the tether path within the Elevator. It does not appear meaningful to send a rescue vehicle when it is always possible to carry the Elevator on the Station (This is a big advantage of the Elevator as a microgravity laboratory over free flyers).

"detachable" Elevator operation sequence

- 1) Retrieve tether.
The tether is retrieved as much as possible (i.e. up to Elevator).
- 2) Detach Elevator.
- 3) Complete retrieval of the ballast.

"hole" Elevator operation sequence

- 1) Retrieve tether.
The tether is retrieved as much as possible (i.e. up to Elevator).
- 2) Repair Elevator or clear tether path.
In some cases this can not be possible (especially if something happens in the cavity inside the Elevator).
- 3) Complete ballast retrieval or cut the tether.

There are some differences between the operation sequences that have to be performed in the two cases. In fact it is apparent that the problem caused by Elevator actuators malfunctioning is somewhat more difficult in the case of the "hole" configuration.

4.3.3

SELECTED ELEVATOR CONFIGURATION

The process of selection among the various Elevator configurations has to evaluate both the problems of the Elevator itself and those caused by it on the Space Station hardware and operations.

Even at a first analysis it is evident that the two configurations which can be considered valid competitors are the "slot" and the "hole" ones. In fact:

- a) The "two modules" configuration does not offer any advantage over the "slot" one and has some problems in the field of payload/service sharing between the two modules.
- b) The shaped tether would require additional hardware and the tether would be more difficult to handle with reference either to the "slot" configuration or the "hole" one.
- c) The unbalanced configuration shows an unacceptable behavior if (relatively) high g missions are foreseen.

For what regards the "hole" and the "slot" configurations, it can be said:

- 1) The "slot" configuration has more problems for what attains more specifically to the Elevator itself

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whereas it offers a more straightforward and simple operations sequence.

- 2) The "hole" configuration simplifies the Elevator design. On the other hand the operations sequence shows that operations themselves would be a big deal (more cumbersome and risky).

Notice that certain facets of the operations could well hide unexpected problems. This is the case for the problem of introducing the tether within the Elevator in both configurations and for the ballast attachment in the "hole" one. Nevertheless sufficient elements are already present to draw a preliminary conclusion.

The "slot" Elevator configuration has been tentatively selected as baseline configuration.

The fundamental considerations to validate this choice can be summarized in two main points:

- a) In the scenario in which we are picturing the VGL use (initial stage of the Space Station), it is probably preferable to choose the more complex "slot" Elevator design with the advantage to simplify the operations, and in turn to minimize the impact of the VGL system on the Space Station.
- b) The potential growth capacity is much larger for the "slot" Elevator configuration which can be easily adapted to a more prolonged or permanent utilization of the Elevator facility in an enhanced Space Station scenario.

4.3.4 ELEVATOR CONFIGURATION CONSTRAINTS

The Elevator configuration and subsystems design are deeply influenced, and in some case driven, by the constraints imposed by the VGL mission itself. A preliminary categorization of these constraints and an estimate of their relative weight are deemed necessary prior to the proper configuration identification.

For clarity we name VGL the overall system (with payload, Space Station interface, mobile component) and Elevator the mobile component of the VGL system.

4.3.4.1 G Level

The most distinguishing feature of the VGL is its capability of achieving various static levels of acceleration (comprehending a near zero level). This feature has an important effect on many Elevator subsystems:

- The structure should be such to transmit the lowest possible disturbance from the tether to the payload.
- The thermal, power and attitude control subsystems should be built with the fewest possible moving components in order to avoid uncertainties on the location of the Elevator CG and mechanical noise due to dynamic effects.
- The non zero gravity can alter the nominal behavior of some components. This is particularly true for equipments involving fluid transfer as for instance heat pipes.
- The mechanisms for Elevator translation along tether should be able to supply the required variable force for the motion along tether and the pressure apt to guarantee the proper interface with the tether itself.

4.3.4.2 Access

The VGL is made as a refurbishable, repairable system. This implies that access should be guaranteed to as many equipments as possible. Two subsystems in particular are required to be easily accessible:

- The mechanism responsible for Elevator translation along tether, which is rather complex and critical. Visual inspection possibility and access have to be guaranteed.
- The power subsystem, if based on batteries power, should allow easy replacement of the batteries in a flexible way. The batteries replacement takes place on the Station or on its immediate proximity with the Elevator being not operative.

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4.3.4.3 Payload Replacement

The VGL payload is assumed to change from mission to mission and there is not a baseline payload to which one can refer to.

To make easy payload replacement, a modular concept may be a valuable solution.

In any case the capability of changing payload has an influence on many subsystems. In fact:

- The structure must be able to accommodate one or more modules containing the payload, in a position as near as possible to CG of the Elevator (which is presumably near to the geometrical center of the Elevator).
- Thermal control, power and data handling subsystems should be able to interface with the payload in a standardized and flexible fashion. This should be relatively easy for the power and data handling, involving only electrical connectors but can be difficult for the thermal control subsystem where physical connection is required.
- The ACS is influenced by the mass properties of the payload. This implies on one hand constraints on the allowable mass properties of the payload, on the other hand requirements on the ability of the ACS to deal with a set of possible mass properties of the Elevator.
- Opportune mechanical interfaces and mechanisms must be provided to permit easy replacement of the payload.

4.3.4.4 Surface Constraints

In order to reduce the structural flexibility of the Elevator, no wings of solar arrays nor of thermal radiators are foreseen.

In this way the amount of external surface available to the power and thermal control subsystems is limited leading to a specialized design.

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4.3.4.5 Slot Configuration

The design decision leading to a slot configuration is a driver for:

- Structure. The general shape of the structure is almost completely dictated by the slot presence.
- Mechanisms. The mechanisms used for Elevator motion along the tether should be able to engage and disengage a tether which is entered in the Elevator through the slot.

4.3.4.6 Constraints Summary

A pictorial summary of the previous analysis is reported in Fig.4.3-6. A relative weight (from very low to very high) has been assigned to each constraint to give an idea of what we feel to be important for each subsystem. Some items of this evaluation can be not apparent from the above discussion:

- The thermal control and the ACS subsystems need a certain degree of accessibility. The thermal control can require some degree of reconfiguration when the P/L is changed, and there is the need of resupplying attitude control cold gas jets.
- The TT&C system requires a certain amount of surface (or more correctly Space Station visibility).
- The star/sun sensors of the ACS require an unimpeded field of view.

It can be seen that the structure is singled out as the most constrained subsystem, which is another way of saying that the structure depends strictly on the unique mission of the VGL.

The other subsystems which are critical are the thermal control, power and mechanisms. The ACS does show some peculiar problems whereas the TT&C and the OBDH appear quite standard design.

The graph in Fig.4.3-7 shows what is the assumed order of importance among the various constraints on the Elevator design. It is noticeable that the most important constraint is the VGL ability to replace payload.

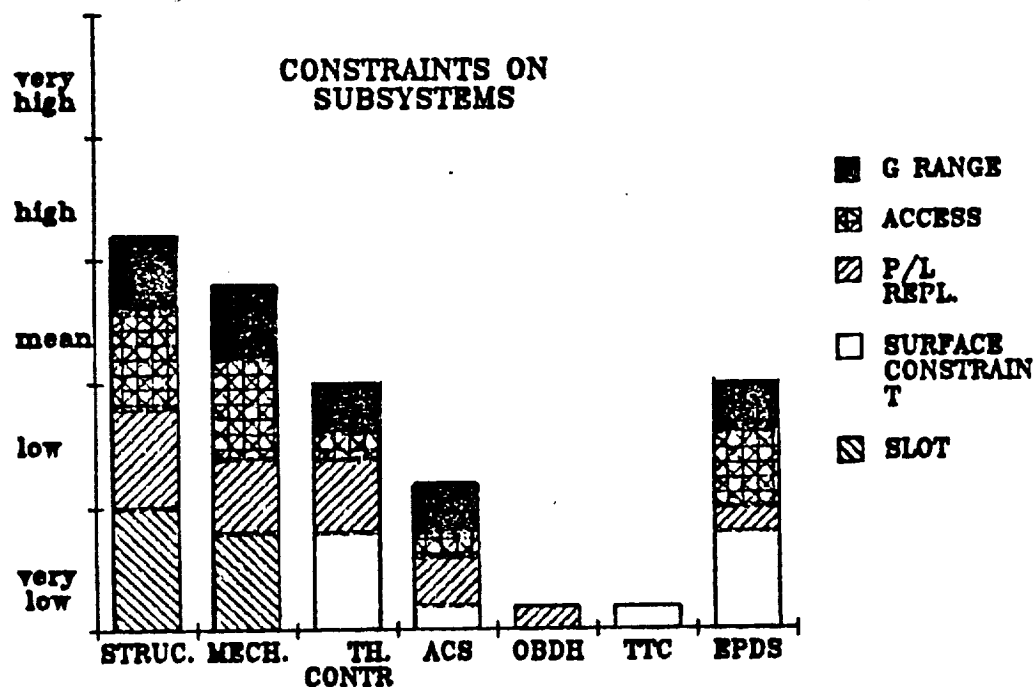


FIG. 4.3-6 ELEVATOR SUBSYSTEM CONSTRAINTS

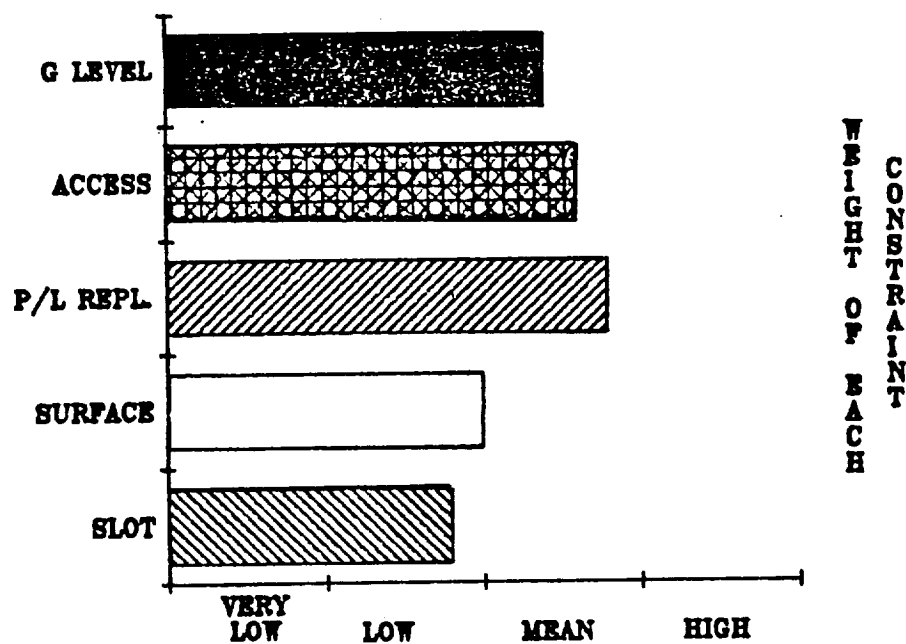


FIG. 4.3-7 ELEVATOR CONFIGURATION CONSTRAINTS

4.3.5 PAYLOAD MODULE

As shown in the previous section the problem of replacing the payload is of paramount importance to the VGL conceptual design. So in the following an outline of the payload problems is made and design decisions are suggested.

4.3.5.1 Payload Location

The payload location and size are almost completely determined by the condition of achieving a maximum value of 10^{-6} g ($= 1 \mu\text{g}$) all over the payload when the Elevator is on the CG of the whole system.

The gravity gradient acceleration is given by:

$$a_x = 0$$

$$a_y = -n^2 y$$

$$a_z = 3 n^2 z$$

$$n = \text{mean orbital motion} = 1.14 \cdot 10^{-3} \text{ sec}^{-1}$$

So the volume into which the gravity gradient is less than 10^{-6} g is an elliptical cylinder with the semi mayor axis being $a = 7.5$ m and semi minor axis $b = 2.5$ m. The center of the ellipse is on the overall CG.

The desired level of $1 \mu\text{g}$ can then be obtained keeping the payloads and overall CG as near as possible, with all the payloads located within the above mentioned envelope.

It is possible to think to a system where the payload CG does not coincide with the Elevator one, but that would make things more complex as the payload mass could be different for each VGL mission; the Elevator CG would change increasing difficulties in the design of the ACS and in the determination of the desired nominal position of the Elevator.

So the baseline choice is that the payload and Elevator CG's have to be coincident. This implies that the payload has to be located in a position which is somewhat within the Elevator.

Apparently there is ample room for the payload. In reality there are other sources of acceleration to be considered if one wants meaningful results.

First of all there is the acceleration due to aerodynamic drag which is of the order of $0.3 \mu g$. Acceleration due to the attitude motion is more difficult to assess. We can say that it increases linearly with the distance from the CG but its value can be obtained only after thorough analyses and simulations. We can assume, for the sake of simplicity, that the accelerations along the three axes are given by:

$$a_x = -a_d + a_a x$$

$$a_y = -(n^2 + a_a) y$$

$$a_z = (3 n^2 + a_a) z$$

where:

a_d = drag acceleration

a_a = acceleration due to attitude motion for a point at 1 m from the CG

Depending on the sign of the acceleration due to attitude motion, and on the presence of the drag constant acceleration, the ellipsoid representing the zone within $1 \mu g$ is shown in Fig.4.3-8 a,b and c. The intersections of this ellipsoid with the planes $z=0$, $y=0$ and $x=0$ are pictured for various levels of the acceleration due to attitude motion.

In Table-4.3 the maximum distances at which a point may be, still meeting the $1 \mu g$ requirement, are reported.

ROTATIONAL ACC. AT 1M FROM CG (μg)	X (M)	Y (M)	Z (M)
0.10	7.0	4.1	1.9
0.20	3.5	2.9	1.6
0.30	2.3	2.2	1.4
0.40	1.7	1.8	1.2
0.50	1.4	1.5	1.1
0.60	1.2	1.3	.96

TABLE 4.3

In addition, other noise sources should be considered as longitudinal tether vibrations, mispositioning of the Elevator on the tether, pendulum-like tether motion.

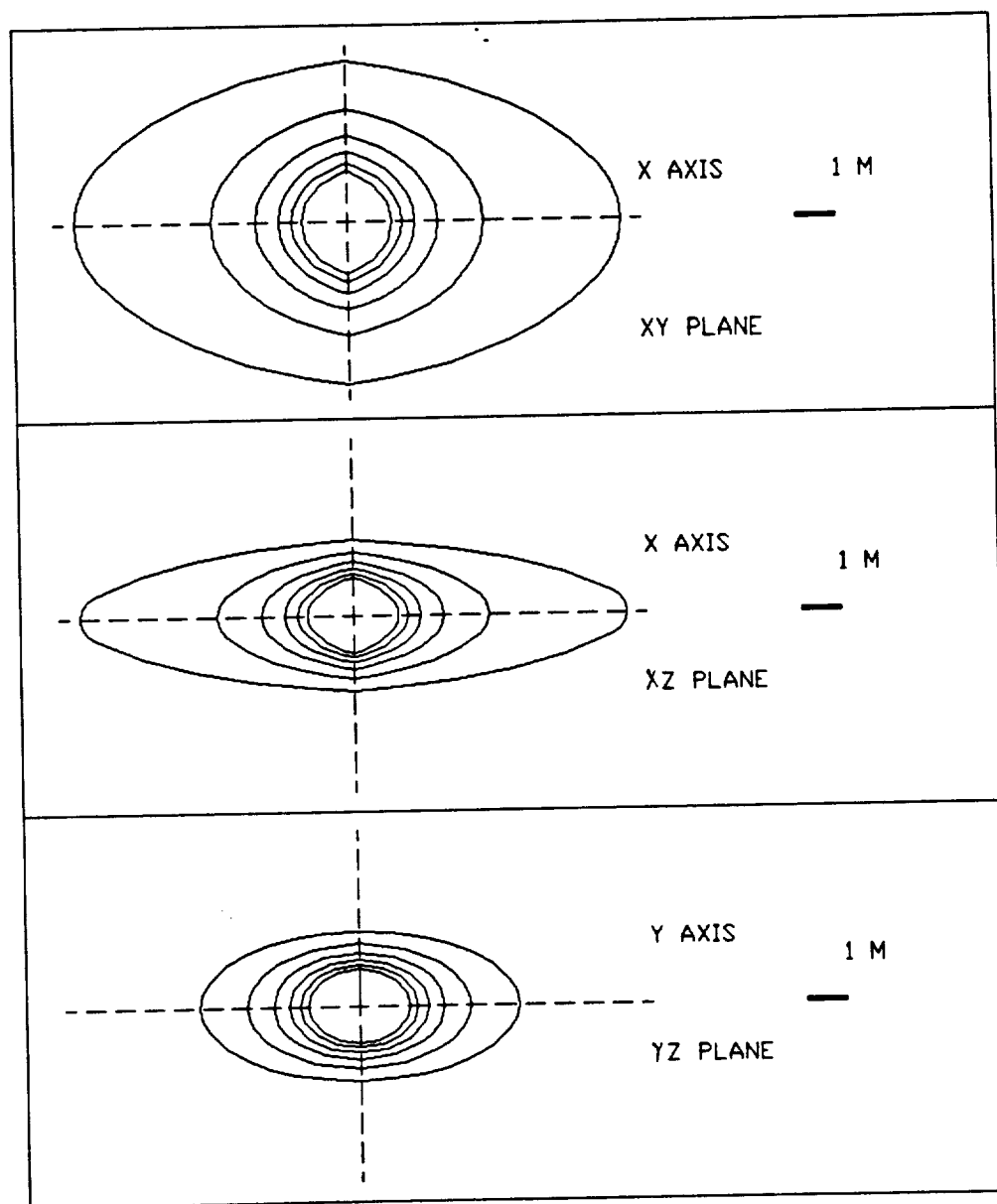


FIG. 4.3-8 MICROGRAVITY ENVELOPES
(A_a ranging from 0.1 to 0.6 μg at 1 m)

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Other considerations reduce the amount of space available. It is reasonable that a 0.25 m radius zone around the tether is negated to the payload and further space is taken away for the presence of the slot.

What is the amount of space that we reasonably need for the payload? This is not so easy to say, but as a guideline we can assume a packaging density between 100 and 300 Kg/m³, for a payload mass between 500 and 1000 Kg. This results in something between 1.6 and 10 m³, with a reasonable value of 4 m³ as baseline (geometrical average).

4.3.5.2 Payload Configuration

Basically two choices are possible for the payload conceptual configuration: payload racks or payload module.

In the first solution, some racks are mounted on the Elevator, each able to house relatively small experiments. As most of the scientific activities will involve the processing of identical samples at various g levels, this choice has some merit.

From the VGL point of view this implies the presence of multiple interfaces between the Elevator and the payload, which is obviously burdensome. Another drawback is the fact that standardization of the racks reduces the flexibility of the system (only experiment up to a certain size may be housed).

The payload module solution foresees a single large module which can be mounted on the Elevator as a whole and has a single interface with the Elevator. The main advantage of this solution relies just in this interface simplification. The flexibility of the system is increased as the constraint on the size of the experiments is greatly relaxed. Another point worth to notice is the fact that if the VGL mission is used for a single class of experiments, the payload module can be specialized to a large degree with an increase on the mass and volume efficiency. From the operational point of view the payload module requires the same amount of operations that would be required just for a single experiment rack; on the other hand the payload module would be a rather bulky object when compared to the single rack experiment, making each operation more complex (notice that the payload module could be made by two or three sections). The interface with the Elevator thermal

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control subsystem appears very difficult if fluid transfer is required. Right now, the best solution appears to be the one in which the payload module is able to handle its thermal control using the Elevator only as a shield and power source for the heaters. Possibly there can be a cold plate on the Elevator which can act up to a certain point as an heat sink for the payload. In this way the Elevator thermal control subsystem can be kept simple avoiding over-design in the effort of dealing with all the possible situations. As last point it has to be said that the payload module could be configured (if the need arises) as a removable rack offering a compromise between the two solutions.

Weighting the relative merit of each solution it has been decided that the payload module configuration offers the best potential for exploiting the VGL capabilities.

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4.4 CRITICAL ELEVATOR SUBSYSTEMS

4.4.1 ELEVATOR/TETHER INTERFACE AND TRANSLATION CONTROL

In this chapter the possible options for the physical interface between Elevator and tether are compared and a preliminary definition is performed.

4.4.1.1 Elevator Motion Analysis

In the SAO analysis a baseline control for the Elevator motion has been found. We have taken that control and adapted it to the most demanding Elevator motion case, that is, the motion from near the ballast to the CG.

The equations defining the motion are:

$$L_C = L_C' \cdot [\tanh(a \cdot t)]^y$$

(for the first phase $t < t_A$)

$$L_C = L_C' \cdot [\tanh(a \cdot t_A)]^y + L'' \cdot (t - t_A) / (t_B - t_A)$$

(for the second phase $t_A < t < t_B$)

$$L_C = L_{tot} - L_C' \cdot [\tanh(a \cdot (t_{tot} - t))]^y$$

(for the last phase $t > t_B$)

where:

L_C = travelled tether length as a function of time t

L_C' = travelled length during hyperbolic tangent phase

L_C'' = travelled length during the constant speed phase

L_{tot} = total travelled length = 10340 meters

t_A = time when the maximum speed is reached

t_B = time at the end of the constant speed phase

t_{tot} = total travel time

y = control parameter that rules the steepness of the motion. A value of 5 was selected as the best one by SAO

a = time constant (sec^{-1}).

A parametric analysis of the effect of changing the time constant "a" has been performed to understand what are the required performances of the Elevator actuators.

In Fig.4.4-1, Fig.4.4-2 and Fig.4.4-3 the trend of the relative distance, speed and acceleration between the Elevator and the CG is reported with $a=1/5200$, $1/2600$, $1/1300 \text{ sec}^{-1}$ (the choice of these values was dictated by the exigency to cover a significant speed range). There is a small difference with the equivalent plots made by SAO, as the travelled length is something different from what we report, as the overall CG is moving along the tether due to Elevator motion. As a first approximation (if we discard terms higher than the first in the gravity gradient expansion) the overall CG does not move along the local vertical.

From the equation:

$$M_e \cdot (A_z - 3 N^2 \cdot Z) = F_a$$

where:

M_e = Elevator mass

A_z = acceleration along local vertical (with reference to CG)

Z = coordinate along local vertical (with reference to CG)

F_a = actuator force

the actuating force (See Fig.4.4-4) and hence the required power can be deduced (see Fig.4.4-5).

Main observations which can be made are:

- 1) The force requirement for the actuators is substantially the one due to the gravity gradient effect; only at the start and at the end of the quickest Elevator transfer maneuver, there is a significant departure of the value of the force from its static value (i.e. from the value dictated by the gravity gradient). In fact the maximum value of acceleration is approximately 4 mm/sec^2 corresponding to an inertial force of 8 N.
This means that the maximum required force for the actuator does not depend (much) on the particular value of "a".

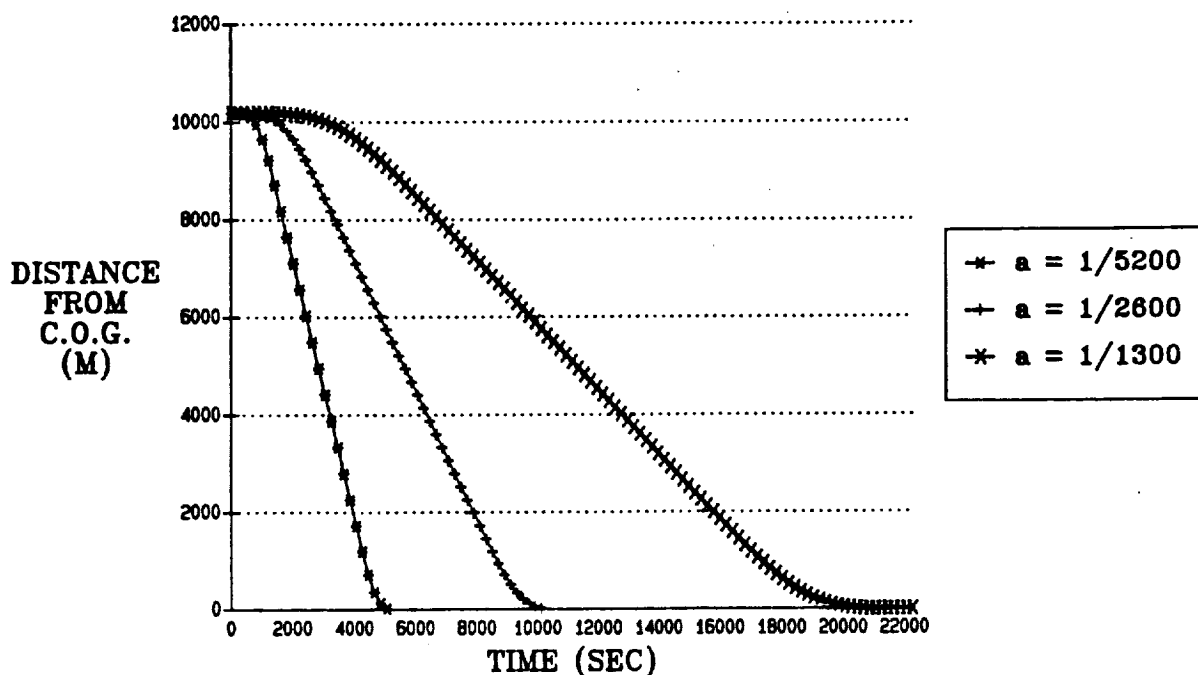


FIG. 4.4-1 ELEVATOR POSITION VS. TIME FOR THREE VALUES OF THE TIME CONSTANT

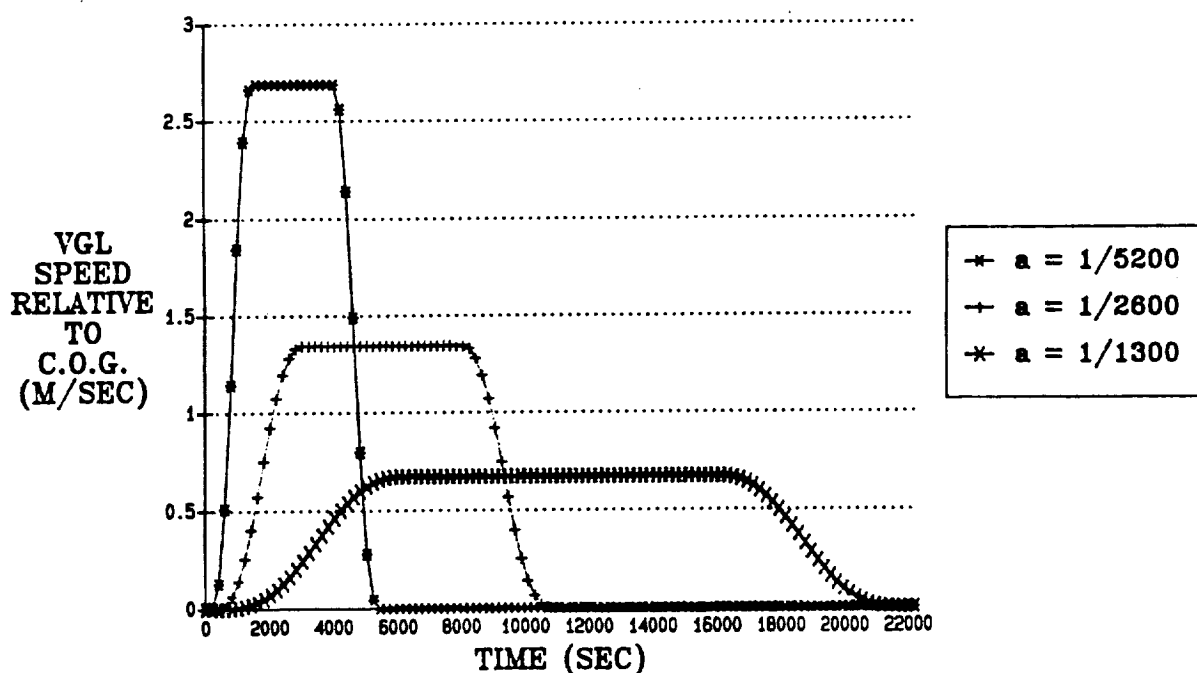


FIG. 4.4-2 ELEVATOR SPEED VS. TIME FOR THREE VALUES OF THE TIME CONSTANT

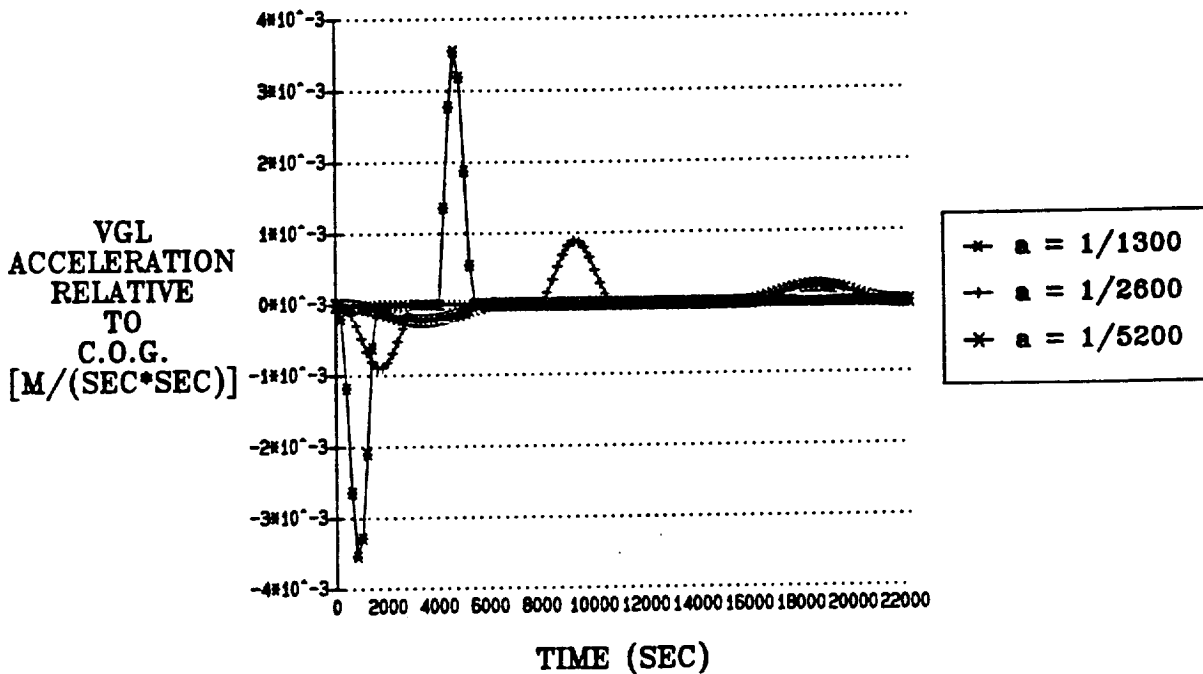


FIG. 4.4-3 ELEVATOR ACCELERATION VS. TIME FOR THREE VALUES OF THE TIME CONSTANT

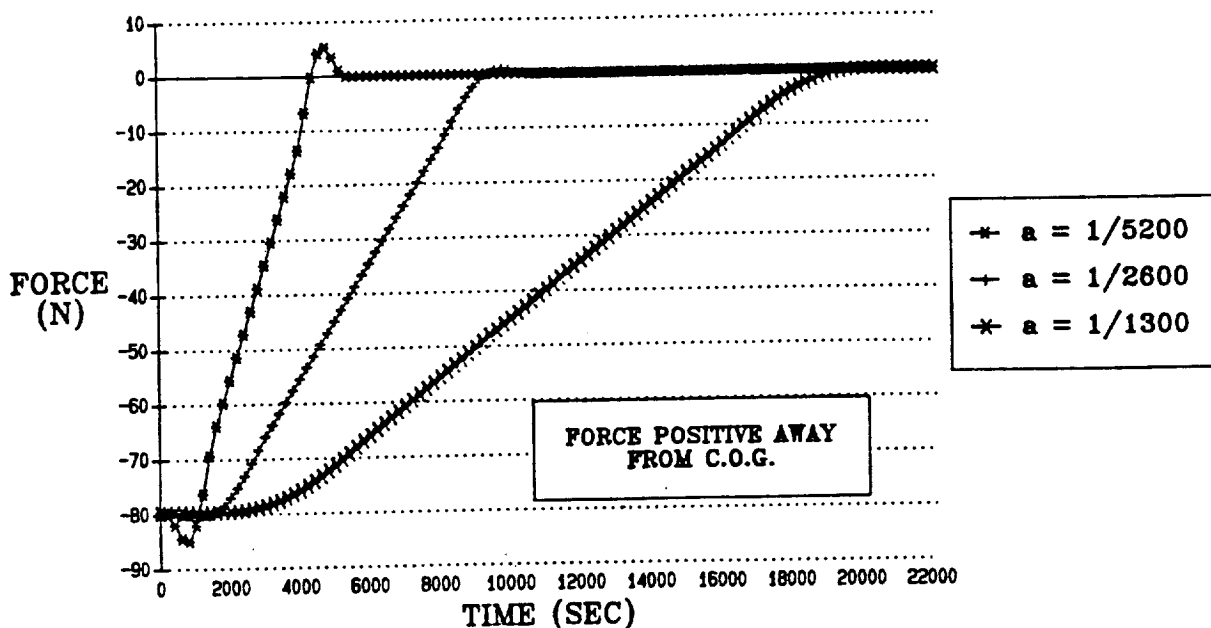


FIG. 4.4-4 REQUIRED ACTUATOR FORCE

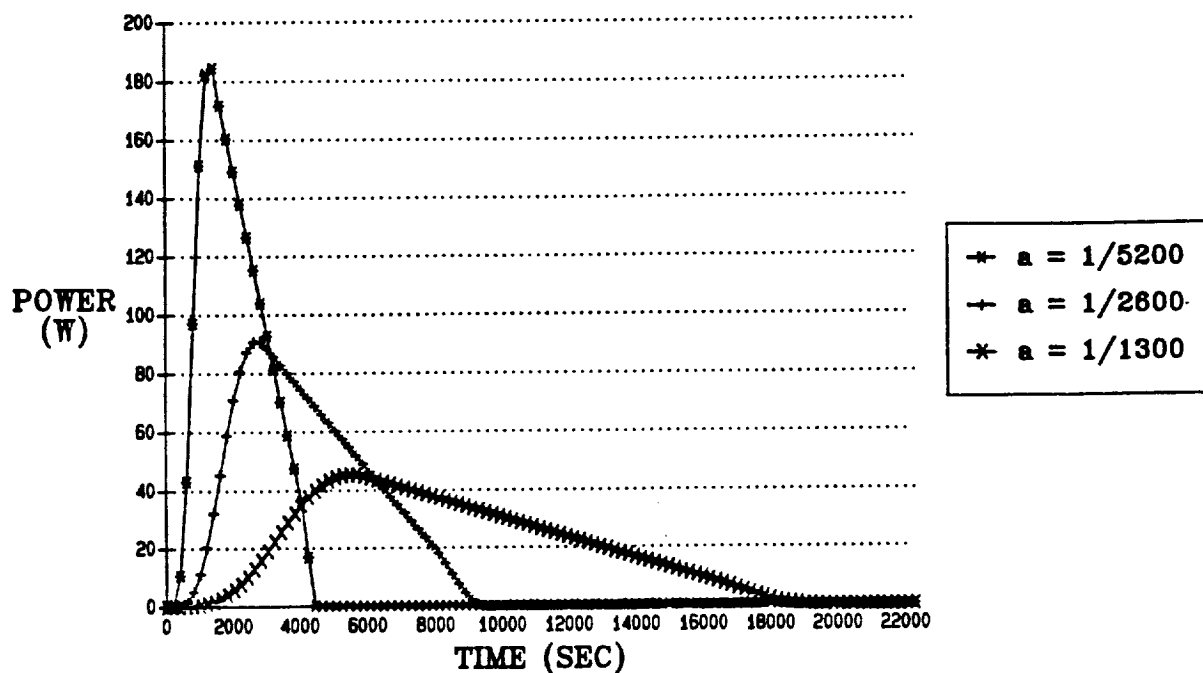


FIG. 4.4-5 REQUIRED ACTUATORS POWER

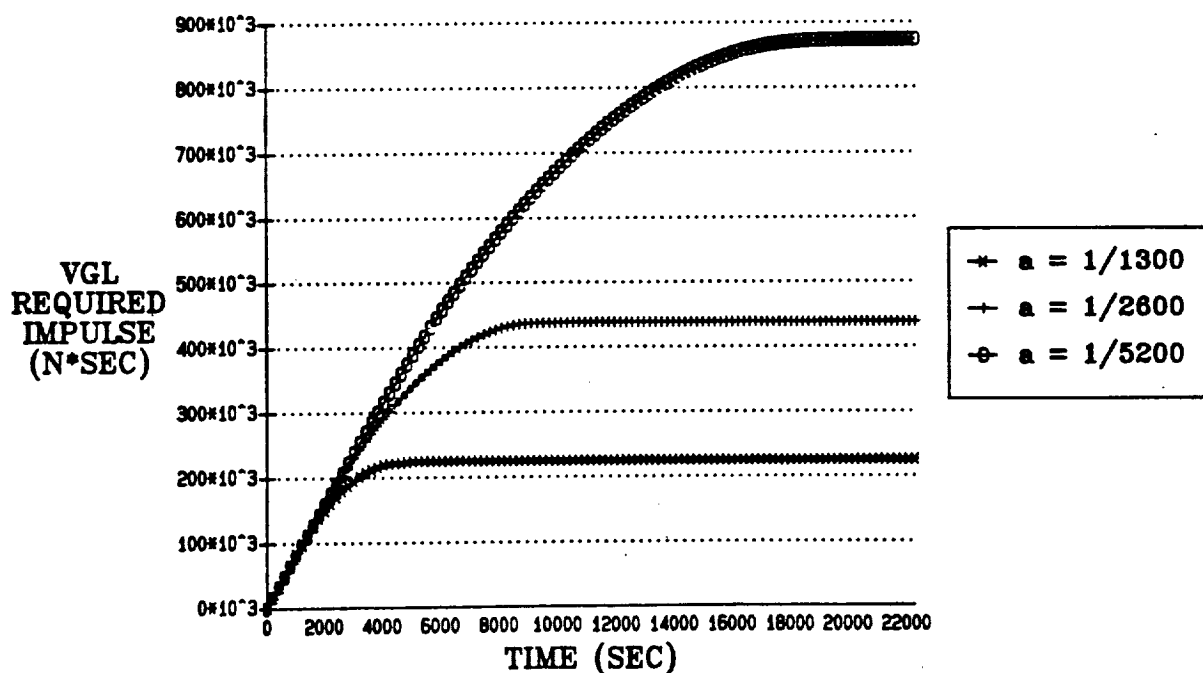


FIG. 4.4-6 REQUIRED IMPULSE FOR A TRANSFER MANEUVER

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- 2) The power requirement on the other hand is very much dependant on the value of "a". The quickest Elevator motion would require power exceeding 180 W which is most likely an excessive value. Power requirement between 100 and 50 W appears reasonable and would lead to a transfer time between 150 and 350 minutes which is still acceptable.

The energy spent in the transfer is the same in all the cases and it is of the order of 115 Wh (410000 J).

4.4.1.2 Actuator Concepts

Having a clearer picture of the force and power requirements, several concepts to realize the motion can be analyzed. Some kind of mechanical brake is in any case required to keep the Elevator fixed on the station point. This is not dealt with in this paragraph.

Three are the alternatives which appear sensible:

- 1) Jets propulsion
- 2) Electromagnetic propulsion
- 3) Mechanical propulsion

4.4.1.2.1 Jets Propulsion

The normal way of moving things in space is by use of jets. First thing to be evaluated is the total impulse that the maneuvers along the tether require.

The integral of the force along the time gives us the impulse. The required impulse for a transfer maneuver is reported in Fig.4.4-6.

The fact that the total impulse depends on the maneuver (unlike the total energy) is natural. In fact it is possible to act in a non-conservative way even if the field of external forces is conservative (it is sufficient to think to a firing rocket hovering without moving under the action of gravity).

In order to spend the least propellant a quick maneuver is required, but this is the maneuver causing the biggest disturbances.

In any case there are two options available for the propellant:

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- a) Cold gases. With a specific impulse of 50 to 60 sec. the propellant mass required would be of the order of many hundreds of Kg so this is not a viable option.
- b) Hydrazine. With a specific impulse of 280 to 300 sec. the propellant mass can be as low as 75 Kg which would be an acceptable value. The problem with hydrazine is the hazards it presents. In fact the hydrazine thrusters should be placed as near to the CG as possible to avoid possible unbalance problems due to thrusters misalignment. The effect of hydrazine on tether fabric cannot be established without a clear identification of material, but undoubtedly it is not beneficial. For Elevator operations in Station proximity the thrusters are firing toward the Station, and this is scarcely acceptable.

A last point which has to be considered is the fact that the location of the overall CG is an unstable point for the Elevator. In fact the gravity gradient force pushes away the Elevator from that point unless the Elevator is exactly on it. This means that we cannot rely on the Elevator "falling" on the right point, but we have to control it accurately with a means like thrusters, which inherently presents problem of finite resolution of the firing impulse.

4.4.1.2.2 Electromagnetic Propulsion

Conceptually there are some possibilities of exploiting electromagnetic effects to move the Elevator along the tether.

This idea requires that the tether is filled with permanent magnets or at the very least with some kind of magnetic material.

In our scenario of temporary, occasional use of the VGL, the cost (both in terms of money and development) and the likely fragility of such a tether do not appear consistent with the general underlying VGL design philosophy. Moreover, the feasibility itself of this concept has to be demonstrated and the large magnetic field which would be created could be not acceptable from experiments point of view.

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4.4.1.2.3 Drive Mechanisms

Here for drive mechanisms we mean all the actuators which, involving direct physical contact between the Elevator and the tether, exploit the friction forces to move the Elevator along the tether.

First of all there are two functions which must be accomplished by any kind of actuator and precisely: the capability of keeping the VGL in a certain position on the tether for long time (up to some weeks), and the capability of keeping the tether at a certain distance from the Elevator cavity walls.

Due to the friction forces between the tether and the drive mechanisms, there is always a certain amount of wear. This can be minimized by proper design of tether and drive mechanism materials.

The propulsion source is the electrical energy carried by the Elevator itself and, since the amount of energy spent during transfer is relatively small, the possible Elevator autonomy is very large (potentially unlimited if solar arrays are present).

4.4.1.2.4 Actuator Selection

Drive mechanisms have been tentatively selected as actuators for the Elevator motion.

There is not really a choice to be made among the various alternatives, as the jet use is too much penalizing in terms of propellant mass, and the electromagnetic propulsion appears to present a too large impact on tether configuration and system complexity.

The main problem for the drive mechanism design is the reduction of wear (especially for the tether).

4.4.1.3 Drive Mechanism Concepts

4.4.1.3.1 Robotic Concept

As first example of a possible actuating mechanism a robotic concept has been considered.

The system under consideration is mainly composed by two pincers moved by a worm and internal thread set. Each pincer grasps the tether alternatively during its stroke as shown in Fig.4.4-7.

The pincers are synchronized in order to achieve the smoothest possible motion, but sharp variations of the tension on the portion of the tether between the two pincers are almost unavoidable.

The main advantages of this concept are:

- 1) The precision of motion which can be achieved using the worm gear.
- 2) The mechanism grasps the tether outside the Elevator, and this simplifies tether hooking, mechanism maintenance and in general all the operations which require visual inspection.

The major drawbacks are:

- 1) The motion in any case has a strong periodic component which causes disturbances and excites tether longitudinal vibrations.
- 2) The complexity of the control system is evident given the requirement on synchronization.
- 3) Even a single failure in tether grappling can lead to dangerous consequences.

4.4.1.3.2 Three Wheels Concept

Another possible concept to drive the Elevator along the tether is that of using two sets of three wheels placed externally at the top and bottom of the Elevator. The conceptual layout of this system is given in Fig.4.4-8.

Each drive mechanism is composed of three wheels, one of which can rotate about the yaw axis by operation of an electric motor coupled with a worm gear set. The force induced by this wheel is equally distributed to the other wheels driving the Elevator along the tether.

The first set, named Translation Drive Mechanism (TDM), has an electric motor that acts directly on the drive wheel, while the second set, named Guide Drive Mechanism (GDM), acts only as a guide for the tether.

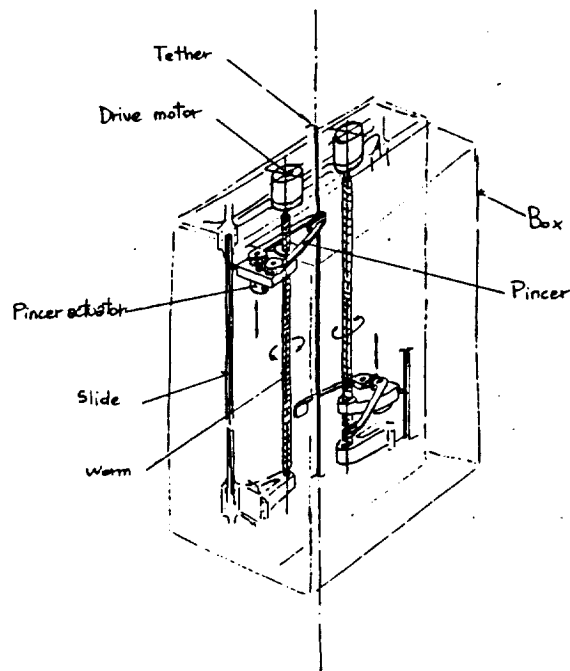


FIG. 4.4-7 ROBOTIC CONCEPT

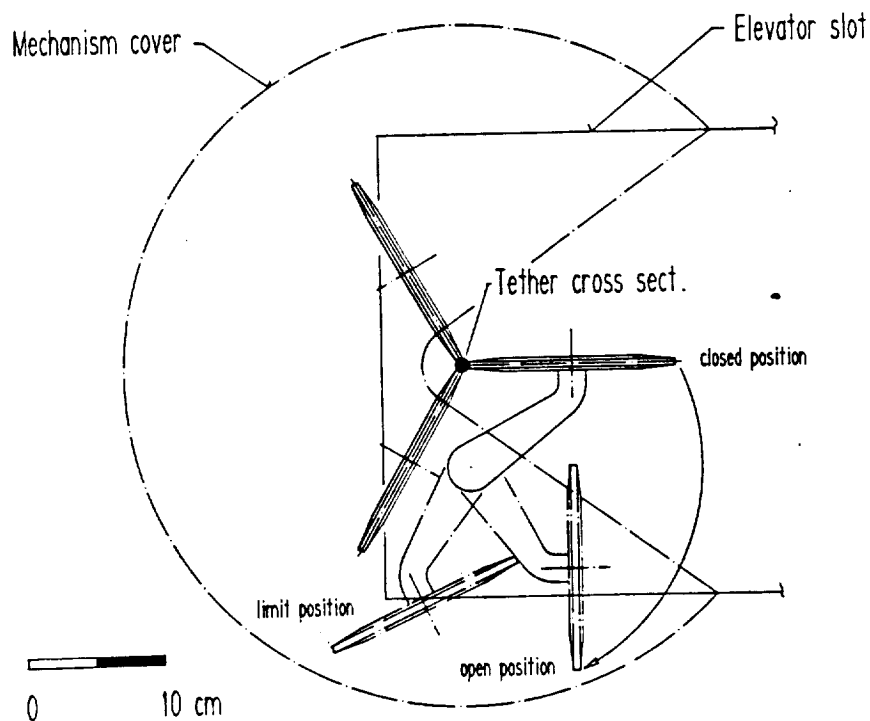


FIG. 4.4-8 THREE WHEELS CONCEPT

On the Guide Drive Mechanism it is mounted a brake which is used during station keeping phase to keep the Elevator at rest in the desired position.

At least the motor wheels (but most likely all of them) should be mounted on springs in order to reduce undesired transient loads on the tether due to dimensional imperfections.

Also to reduce the loads on the tether a soft material with high friction coefficient (rubber) should be used to cover the wheels contact surfaces.

The problem for this system may arise from the fact that the contact area is rather small and hence the stress on the tether can be large. However, the simplicity, the easy access and visibility of the interfaces, single out this solution as very interesting.

4.4.1.3.3 Cog Belts Concept

In order to reduce the localized stresses on the tether the use of cog belts is possible.

This concept uses two cog belts grasping the tether in between as it is shown in Fig.4.4-9.

In this way we distribute the pressure along a certain extension of the tether.

Referring to the above Figure we see that the cog belts are mounted on a triangular pulley and are pressed together by means of sliding blocks. The power is transmitted at the system by means of a worm gear set. This choice guarantees the motion irreversibility.

There are two sets of cog belts placed at the top and bottom of the Elevator (not in the interior of the Elevator cavity to reduce the accessibility and visibility problem).

In general this solution appears to be more complex (think to problem of avoiding tether slipping in the direction outside the plane of the belts) and somewhat less reliable than the three wheels concept.

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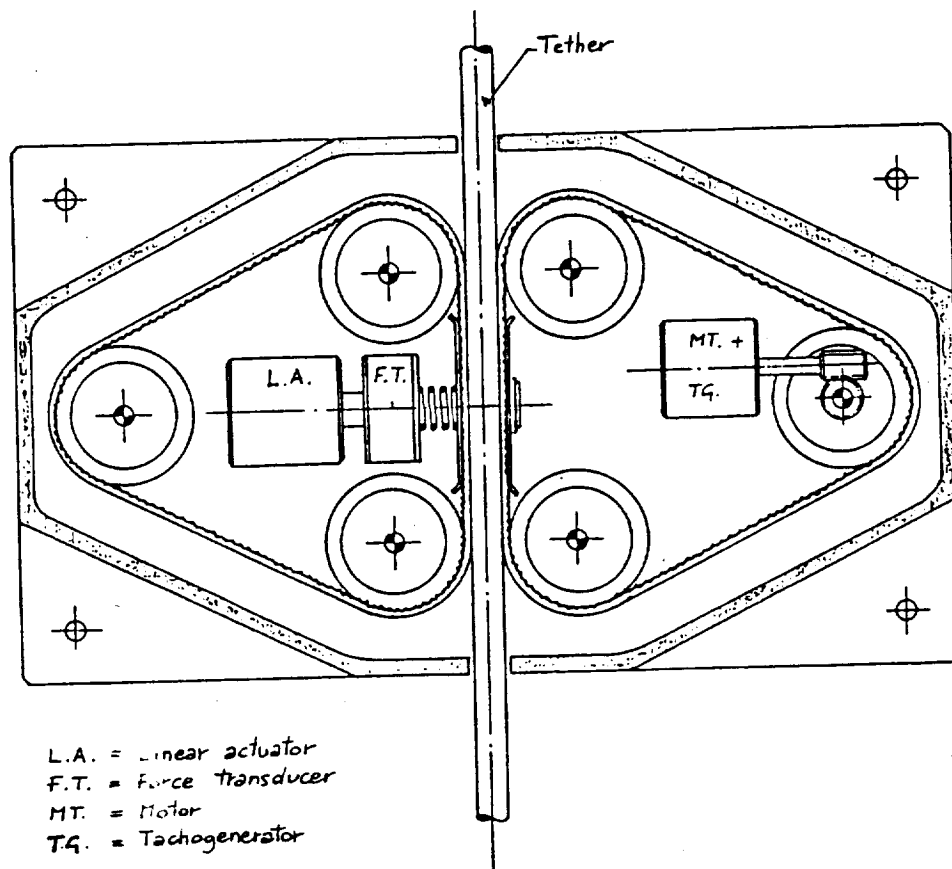


FIG. 4.4-9 COG BELTS CONCEPT

4.4.1.3.4 Drive Mechanism Selection

The concept selected for configuration purposes is the three wheels system which seems more simple especially for what regards the problem of tether hooking. The problem due to localized stresses has to be analyzed and the cog belts concept could be reconsidered in the future. The robotic system, involving complex hardware and causing alternative excitations in the tether during a motion which should be as smooth as possible, is not really a competitor.

4.4.1.4 Cavity Size

The tether requires a certain clearance to avoid rubbing against the wall of the Elevator cavity through which it travels.

The problem lies in finding what is the presumable maximum displacement of the tether within the Elevator under the forces that are due to dynamic effects.

An evaluation of order of magnitude of these forces can be done estimating the value of the Coriolis force which pushes the Elevator along the orbital speed direction.

For the range of Elevator speed along the tether which is of interest (1 to 2 m/sec) the maximum force is:

$$F_C = 2 \cdot N \cdot V \cdot M_e$$

where:

$$N = \text{mean orbital rate} = 1.14 \cdot 10^{-3}$$

$$V = \text{Elevator speed} = 2 \text{ m/sec}$$

$$M_e = \text{Elevator mass} = 2000 \text{ Kg}$$

$$F_C = \text{Coriolis force} = (\text{approx}) \quad 4.6 \text{ N}$$

The maximum deflection of the tether within the Elevator (for a given material and diameter of the tether) depends on:

- 1) The applied load.

- 2) The free suspension span of the tether within the Elevator.
- 3) The tension in the tether and hence the position of the Elevator along the tether.

Notice that the tension in the tether changes drastically near the contact point(s) of the Elevator. In fact if we think to the tension in the tether immediately before the Elevator (starting from the CG), this has to balance the force due to the ballast, the remaining portion of tether and the Elevator; whereas the tension immediately after the Elevator has to balance the force due to the ballast and the remaining portion of tether only. The dimension of this change in tension can be appreciated examining Fig.4.4-10 where the tension along the tether for various Elevator positions is reported. For a quantitative analysis we assume that the Elevator has two points of contact with the tether located at its top and bottom but only one of the them is able to exchange forces along the tether axis. Now assuming also that the maximum acceptable displacement is 0.1 meter, we want to know the force that if applied on the center of the tether portion within the Elevator, would cause such a displacement.

The answer is shown in Fig.4.4-11 for different sizes of the Elevator and in the two cases for tether attachment (longitudinal loads exchanged in the contact point toward the Space Station or in the contact point toward the ballast).

The required loads, if there is not tension, are:

ELEVATOR	
HEIGHT (M)	LOAD (N)
1.0	82
1.5	25
2.0	10

It can be noticed that the tension gives rise to a substantial increase in tether stiffness and that there is a large difference between the values representing different contact modality for the same Elevator height (this last is assumed to be equal to the free span of the tether within the Elevator).

When the Elevator is attached on the contact point toward the ballast the computed force increases as the Elevator distance from Space Station increases; that is

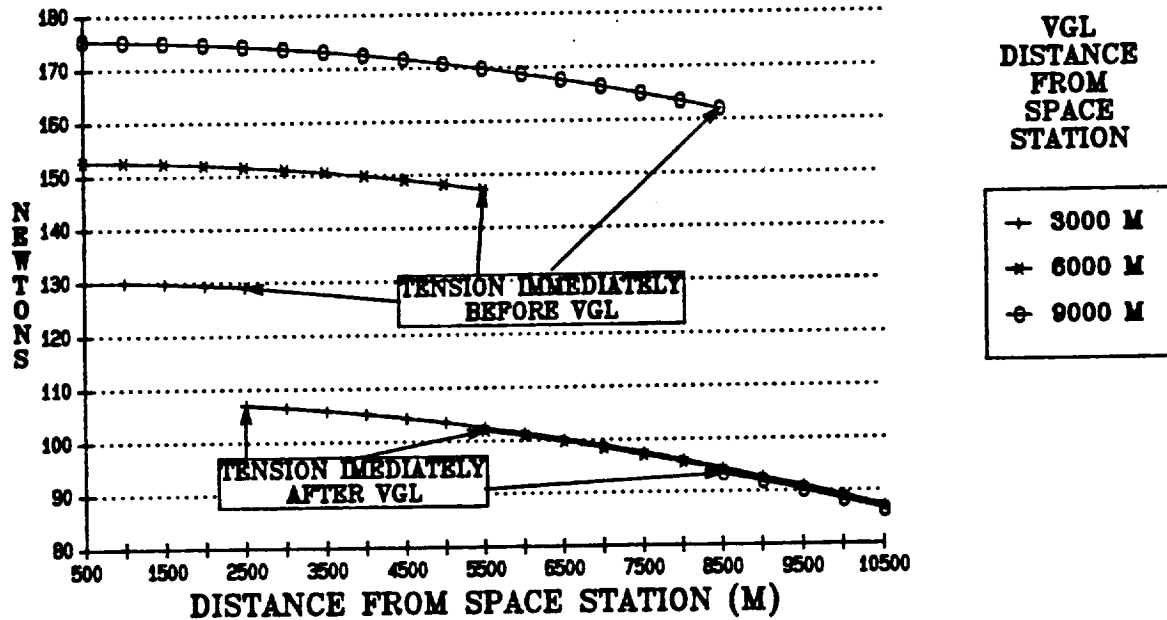


FIG. 4.4-10 TETHER TENSION BEFORE AND AFTER ELEVATOR

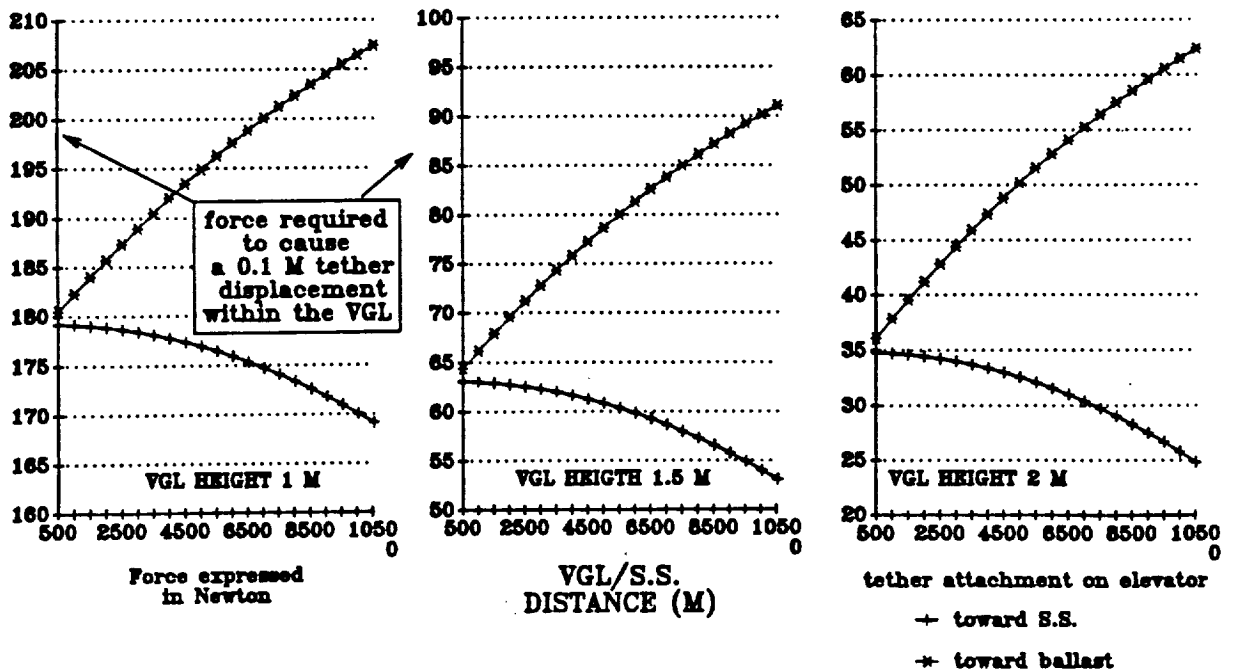


FIG. 4.4-11 FORCE REQUIRED TO CAUSE A 0.1 m TETHER DISPLACEMENT WITHIN ELEVATOR

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due to Elevator induced tension which is greater the farther the Elevator is from the Space Station. On the other hand, if the Elevator is attached on the contact point toward the Space Station, the force due to the remaining tether portion is diminishing (there is less tether) and that explains the trend shown in the graphs.

The indications which can be drawn by the above results are:

- 1) Keep the free span of the tether within the Elevator to a minimum.
- 2) Attach the Elevator on the tether in such a way to keep the maximum possible tension within the tether. This is important if a relatively large free span of tether is unavoidable.

In any case the computed force is much larger than the maximum Coriolis force due to Elevator motion, so this problem does not appear to be particularly worrisome and the size of the hole would be probably dictated by the operational problems. A diameter of 0.3 m appears to be a sensible minimum value.

4.4.2 POWER SUBSYSTEM

The electrical power subsystem is one of the main design drivers for the VGL being quite massive and bulky. In addition, the possible use of solar arrays has a profound influence on other subsystems, mainly the ACS subsystem (if a sun-pointing attitude is required) and on the availability of the external surfaces (important for the thermal control).

A proper evaluation of the power required from service and payloads is quite difficult right now but some guesses can be made. In particular it is possible to establish an envelope of average power consumption and mission duration. Power peaks should be dealt with a proper management of the energy flux. The range that we think meaningful at this time is :

- o Average power consumption from 200 to 600 Watt (sub-systems + payload).
- o Duration of the Elevator mission from 7 to 30 days.

An important point which must be underlined is the fact that although the experiment duration can be quite long, this does not necessarily mean that no refurbishment at the Space Station is possible during this period. Refurbishment during the experiment is obviously quite complex and "expensive" operationally (even if at most only some hours are required to the Elevator to reach the Space Station), and it would be best to avoid it if possible, but this let us choose a power subsystem of reasonable size and resort to mid-experiment refurbishment in particularly demanding cases. This is a typical case where the flexibility of the Elevator is manifest.

Some criteria are necessary for the comparison of the possible sources of electrical power. The parameters of primary importance are (roughly in order of importance):

Mass. This is, as always in space systems, the first parameter to be taken in consideration. The Elevator mass is required to be near to 2000 Kg. Even considering the peculiar condition under which the Elevator operates we think not acceptable a power subsystem mass greater than one third of the overall mass.

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Size. The sheer size of the power subsystem can create a difficult problem of area and volume allocation. This is particularly evident in the case of the solar arrays which otherwise would be the obvious solution.

Cleanness. Here we mean by cleanness the ability of the subsystem to operate with low disturbance and minimum pollution (in any sense: electromagnetic, chemical, etc.) of the payload environment. This is probably the most important parameter. A large effort is going to be spent in the Elevator to create a very special environment in which to perform μg and variable-g experiments. Hence it is necessary a careful attention so that the large energy handled by the power subsystem does not degrade the Elevator environment.

Flexibility. The power subsystem has to be adaptable to the various possible payloads and missions. This means not only that an upgrading capability is desirable but also that if lower power than the maximum available is required, it should be possible to exploit this (enhancing for instance the payload mass).

Other evaluation factors are important (as safety, shelf life, cost, subsystem development risk, reliability) but the points that we want to stress are those in which the Elevator is particularly constrained and/or are peculiar to it.

4.4.2.1 Power Sources

Three are the main possible ways in which power can be supplied and which are discussed in some detail:

Transmission. The Elevator can be supplied by the Space Station if an adequate link is provided. The two basic options are either by a cable or using some form of concentrated radiant energy as microwaves.

Storage. Fuel cells and batteries can store quite a big deal of energy on the Elevator. These systems have a rather large flexibility in handling changing power requirements, but only a limited capability in terms of energy.

Generation. Some systems can be used to generate power on board of the Elevator. RTG's and solar arrays (coupled with rechargeable batteries) are characterized by the availability of an energy almost unlimited, but are

constrained by the limited average power. This problem can be circumvented up to a certain point by a clever power management but it remains the main drawback of this solution.

In the following pages it is shown that the only realistic possibility for variable-g missions is the use of some form of stored energy helped by the solar arrays.

4.4.2.1.1 Transmission

Microwaves or similar means cannot be effectively used to supply power to the Elevator. Conceptually the idea has some advantages: no further physical link between Space Station and Elevator, low power subsystem mass (on the Elevator), access to a source of almost unlimited power (in terms of the Elevator exigencies). The crucial problem is that of the cleanness. It seems really improbable that service and payloads can be shielded effectively from this kind of radiation avoiding unacceptable mass penalties. Another problem is the fact that unavoidably the tether would be irradiated for a prolonged time.

The other way of transmitting power from the Space Station to the Elevator is by a physical link, that is by cable. In the case of variable gravity missions if we use a dedicated cable (not the tether) we have to deal with:

- o cable reeling and unreeling during VGL motion. Operationally this is quite undesirable (increased Space Station role).
- o the problem of avoiding power cable entangling with the tether during VGL motion.
- o another cable which although not necessarily as massive as the tether (the sizing parameter is always the capability to stand to meteoritic damage) can be still quite heavy. This would alter the performance of the system and would add mass to it.

These difficulties seem to make this solution complex and costly in a scenario of limited use of the VGL facility.

It can be possible to use the tether itself as a means of conducting the current. The big obstacle in this case

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is the fact that the Elevator can be in any position along the tether even at 10 Km from the Space Station. High voltage is required to avoid large power loss in the tether and, transformers and AC/DC converters would be required on the Space Station and on the Elevator. Electrical induction could be possibly used to transfer the power from cable to the Elevator without electrical conductor continuity, but (beside the complexity) it is difficult to see how it would be possible to avoid payload interaction with magnetic field so generated.

Another possibility is to use some kind of wiping contact between Elevator and tether. This is perhaps possible but would probably cause unacceptable side effects due to the not insulated current passing through the tether in proximity of the payloads and undesired discharge can be a problem. Tether handling is much more complex and its cost increases. So this solution does not appear to be worthwhile the effort.

4.4.2.1.2 Generation

RTG's (radioisotope thermal generator) are used for spacecraft heading towards the outer part of the solar system and were also used in the past for short manned mission. Their main characteristics are:

- 1) No dependance on solar aspect (thus no attitude control requirement) and in general no dependance on the environment.
- 2) Small but steady power output for long periods.
- 3) Low efficiency of the conversion from thermal to electrical power.

As an example the data for the General Electric GPHS (used in Galileo) are reported:

Mass: 55 Kg
Power output: 290 W (b.o.l.) 250 W (after 5 years)
Efficiency: 6.5 % (approx 4.5 thermal KW are rejected)
Size: 0.42 m (diameter) x 1.13 m (height).

Potentially these data are good (with 2 RTG's, that is slightly over 100 Kg, it would be produced a power exceeding 500 W). The thermal output is of the order of 9 KW and if we assume a radiator temperature of 450 K (as it was in other RTG applications) the Elevator would

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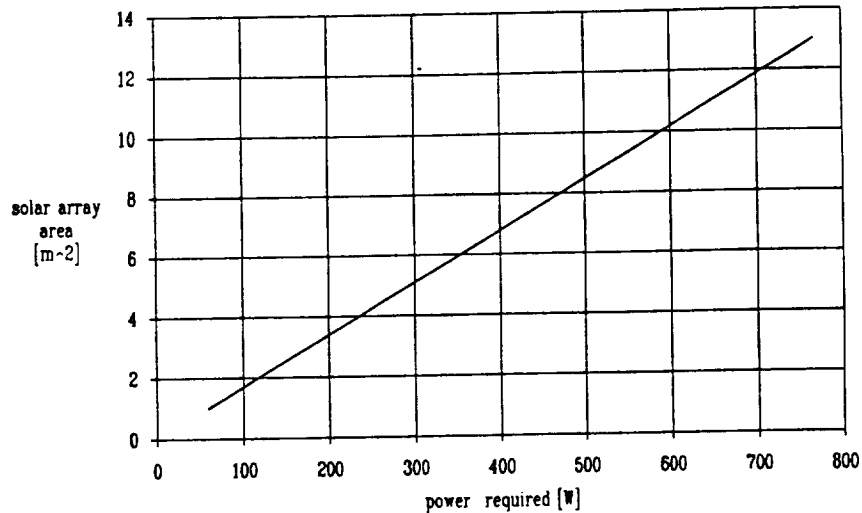
need a radiating area exceeding 4 m² (always looking towards deep space). Heat pipes are possibly not able to handle such a large thermal load and a fluid loop with a pump is then necessary, increasing so the level of mechanical disturbances within the Elevator (notice nevertheless that some of this thermal power can be used to warm the Elevator if that is required). Another drawback of this system is the fact that there is not a shut down capability and this increases storage and handling problems (remember that the VGL should be able to operate as an opportunity payload). The problem of the emission of γ rays and neutrons by the RTG is possibly the worst one, and placement of the RTG outside the spacecraft on a boom is the solution adopted in most RTG designs. We strongly prefer not to use booms on the Elevator in order to reduce to a minimum structural flexibility and hence disturbances due to appendages oscillation. Shield mass is a decreasing quadratic function of the distance and RTG designs are based on the idea of having at least few meters between the RTG and the payload. In the end the conclusion on RTG as a power source for Elevator is quite negative. The basic advantage of extreme compactness and low mass can be lost if booms are not used, operative disadvantages are quite evident and the large thermal load can have a too big impact on the Elevator design.

Solar arrays are the standard power source for most spacecrafts and the main reasons are:

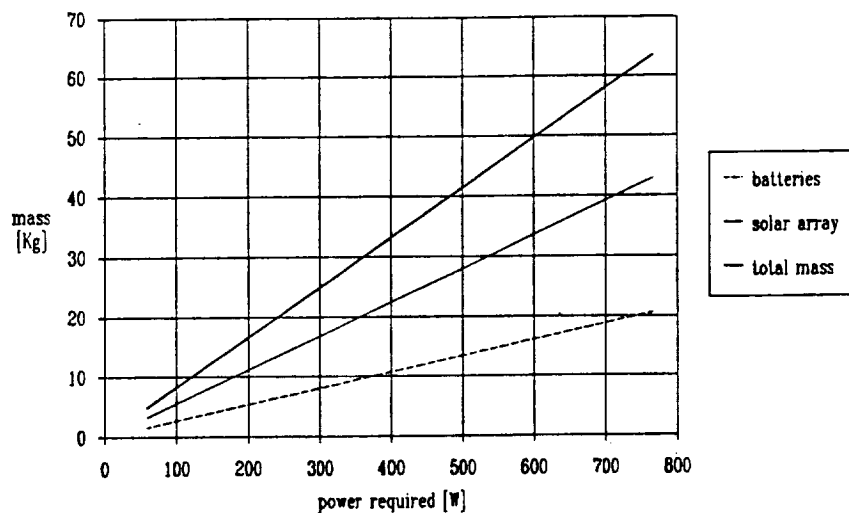
- Good power over mass ratio;
- Potentially long duration;
- Well proven and reliable system.

The main disadvantage of the solar arrays is that they require a relatively large area and that their output is dependent on sun aspect and visibility. In LEO the time spent in eclipse is about 40% of the total time so a relatively large amount of secondary (rechargeable) batteries is needed. In the future the use of rechargeable fuel cells should reduce the energy storage system mass.

The results relative to the solar arrays + secondary batteries system sizing for different power requirements are shown in Fig.4.4-12a&b (GaAs solar cells and Ni-H₂ batteries characteristics have been used for the computation).



**FIG. 4.4-12a SOLAR ARRAY AREA VS. REQUIRED POWER
(90° SOLAR ASPECT ANGLE)**



**FIG. 4.4-12b TOTAL SYSTEM MASS (SOLAR ARRAY + RECHARGEABLE
BATTERIES) VS. REQUIRED POWER**

The main conclusions which can be drawn are:

- The mass of the system is relatively low.
- The required solar arrays area is very large (notice that the calculation assumed a 90 degree solar aspect).
- The batteries mass is about one third of the total mass so their energy density is not really important (that is rechargeable fuel cells are not required in this case).

Even the theoretical required solar arrays area cannot be reasonably accommodated on body mounted solar arrays, so solar panels wings would be required. As already noted, we strongly prefer to avoid appendages on the Elevator design, which in this case would be mobile (to follow the sun) henceforth causing undesired mechanical noise.

4.4.2.1.3 Energy Storage

Two possibilities are competitive as an energy storage system :

- Fuel cells
- Primary (not rechargeable) batteries

Secondary batteries are not considered appropriate in our case as their energy density is an order of magnitude lower than that of both the above mentioned systems.

The first and in a sense the easiest characteristic to be compared between batteries and fuel cells is the mass as a function of the total energy.

The possible amount of required energy can vary by more than an order of magnitude (7 days x 200 W = 33.6 KWh; 30 days x 600 W = 432 KWh).

The case for primary batteries is quite simple; depending on the materials used, the energy density can reach value as high as 480 Wh/Kg in the case of lithium / thionyl chloride batteries. If all the energy comes from the batteries the required mass is slightly over 900 Kg.

The problem for fuel cells is more complex as more variables are present in this case. The main ones are:

- the couple oxidant, oxidizer used;
- the efficiency of the fuel cell (in the range 50% to 70%);
- the storage method for the gases;
- the material used for the tanks.

For a detailed calculation of fuel cells mass and size, especially relevant to tank sizing, see the Quarterly Progress Report # 4.

The main conclusions which can be drawn are:

- The specific energy of the fuel cell power subsystem is satisfactory except for the very worst case (low energy and efficiency). In particular the specific energy is of the order of 450 to 650 Wh/Kg that is equal or better (up to 25% better) than the batteries specific energy.
- The mass of the system is driven by the mass of the tanks; especially the hydrogen tank(s). This is important as it means that only a portion of the mass (approx 30%) is "consumed" during the mission and needs replacement, whereas the batteries are to be substituted completely.

The masses of the hydrogen and its tank, and of the oxygen and its tank are remarkably different causing a balance problem. Moreover fuel cells use implies that there is a mass shifting from the oxygen and hydrogen tanks to the water container. There are in general two problems:

- 1) CG shift along a direction normal to the tether.
We prefer the Elevator CG to lie on the tether to avoid undesired torque (due to tether tension). The only apparent way to solve this problem is by using more than one tank for each gas, placed symmetrically around the local vertical through the CG.
- 2) CG shift along the tether direction.
If during the mission there are large mass shifts along the tether direction it is possible that the μg environment is downgraded. This does not appear an insurmountable problem.

The relative cleanness of these two power sources is difficult to assess at this conceptual level of definition. For what regards the chemical pollution, the two systems, fuel cells and batteries, are probably equivalent (more aggressive components in the batteries, fluid

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motion and hence risk of losses in the fluid loop in the fuel cells). The real difference lies in the fact that most likely the fuel cells induce a certain degree of mechanical noise (fluid pumps). This is something that we want to avoid and the static transformation of chemical energy into electrical performed by the batteries appears the best way to handle the problem.

The batteries appear to be able to offer a better degree of flexibility than fuel cells. In fact it is sufficient to add or eliminate a certain number of units to comply with the mission requirement whereas the fact that most of the fuel cells mass is due to the tanks implies that only a limited flexibility is achievable (unless one is prepared to substitute the tanks themselves). The same considerations can be applied to the possibility of resupplying the Elevator during the mission which seems easier if done by batteries replacing instead of fluid transfer from Space Station to Elevator. Cost is one item of difficult evaluation as the fuel cells while undoubtedly benefit of lower recurring cost (oxygen and hydrogen resupplying vs. batteries replacing), cost surely much more in terms of not recurring cost, due to the development of a dedicated fuel cell plant.

4.4.2.2 Power Subsystem Conceptual Definition

The conclusion which can be drawn at this point is that we prefer to use the batteries instead of the fuel cells, although this implies a mass penalty, in the light of their superior volumetric energy density, flexibility and cleanness.

We decided to go for a batteries system as primary energy source, but this does not mean that a complementary source (solar arrays) cannot be used on the Elevator. There are two good reasons to introduce a relatively small amount of solar arrays in the Elevator design:

- Operational. It can happen that, after the completion of the nominal mission, the Elevator is required to stay on the tether for a prolonged time without the possibility of retrieval. In this case if we rely on the batteries alone, we incur in the risk of creating a temporal limit to the Elevator operational capability that is highly undesirable.

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- Mass reduction. It can be shown that the addition of a small amount of solar arrays can reduce the mass of the batteries especially for low power, long time missions.

The idea here is to use body mounted solar arrays to supply power directly to the Elevator during the sun exposed portion of the orbit. In this particular case, such an arrangement of the solar panels should not cause excessive heating of the cells, even if the Elevator doesn't spin, because:

- 1) the Elevator orbit has a short period (1.53 hours), about 40% of which is spent in eclipse;
- 2) when the Elevator is in sunlight, due to its Earth-pointing attitude, its sides (apart those parallel to the orbital plane) are never continuously illuminated (see also Appendix A of the Quarterly Progress Report #7);
- 3) it can be shown that the illumination angle of the Elevator sides never remains above values of 70° - 80° for more than 8 minutes.

The effective area of solar arrays which should be mounted on the Elevator body and the panels suitable location are analyzed in the relevant section of the Elevator configuration.

A small amount of rechargeable batteries (of the order of few kilograms) is required to provide power during eclipse in an emergency condition.

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4.4.3 ATTITUDE DETERMINATION AND CONTROL SUBSYSTEM

The Elevator represents a special case in terms of attitude control design. In fact:

- o First of all it is not a "free flyer" but it is able to exchange forces and torques with the tether. Around the pitch and roll axes these interactions dominate all other effects.
- o On top of a rather coarse requirement on the pointing, we have a stringent requirement on the angular speed and acceleration which can be tolerated as disturbance to the Elevator gravity level.

So a first analysis of the ADCS is deemed necessary even at this very preliminary stage to clarify the main issues involved.

The reference frame used in the discussion is centered on the Elevator center of mass and its axes have the same orientation of the Space Station reference frame axes:

X axis = flight direction = roll axis

Y axis = out of orbital plane = pitch axis

Z axis = local vertical = yaw axis

4.4.3.1 ADCS Requirements

As already said the requirement on the pointing can be rather coarse being driven mainly by the demands of some equipments as solar arrays (if present), radiators, and communication antenna which should be able to accept pointing errors of the order of some degrees.

In the following we assume that a maximum error of 2.5 degree is acceptable (semi conical angle).

Quite different is the problem posed by the constraint on rotations when translated in terms of angular rates and accelerations.

The requirement stated in Section 3 says that a maximum uncertainty of 1 degree on the acceleration vector direction is allowable.

Even assuming that all the vector misdirection is due to attitude motion, this condition appears to be quite

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stringent (acceleration in direction orthogonal to the tether of the order of 2 hundredth of the residual gravity gradient acceleration). At very low acceleration levels ($10^{-6} \text{ g} = 1 \mu\text{g}$) it is understood that larger values would be negotiable.

For the pitch and roll axes the 1 degree requirement on the acceleration vector can be immediately translated in a maximum pointing error of 1 degree.

In the case of a yaw axis pointing error, there is a very small effect (due to the component of gravity gradient normal to the orbital plane). The maximum acceleration due to this effect is $0.3 \mu\text{g}$ for a point at 1 meter from the tether axis.

The pointing stability is a concern.

Rotations about the pitch, roll and yaw axes cause centrifugal and tangential accelerations.

Admitting that the system is oscillating at a certain frequency f with amplitude δ the total acceleration is:

$$A = R \sqrt{[(\Omega^2 \delta \sin(\Omega t))^2 + ((\delta \Omega \cos(\Omega t))^2)^2]}$$

being:

$$\Omega = 2 \pi f$$

R = distance between tether axis and the point under consideration.

The resulting maximum allowable δ as a function of the frequency f and of the residual gravity level is shown in Fig.4.4-13. It can be seen how stringent the requirement becomes for the high frequencies.

4.4.3.2 External Torques

For external torques we mean all the torques acting on the Elevator excluding that due to the attitude control system.

Tether induced torques

The first torque to be examined and of paramount significance is the torque due to the tether itself. Obviously

CONSTRAINTS ON ROTATION AMPLITUDES DUE TO GRAVITY
LEVEL DISTURBANCE REQUIREMENTS ($R = 1$ m)

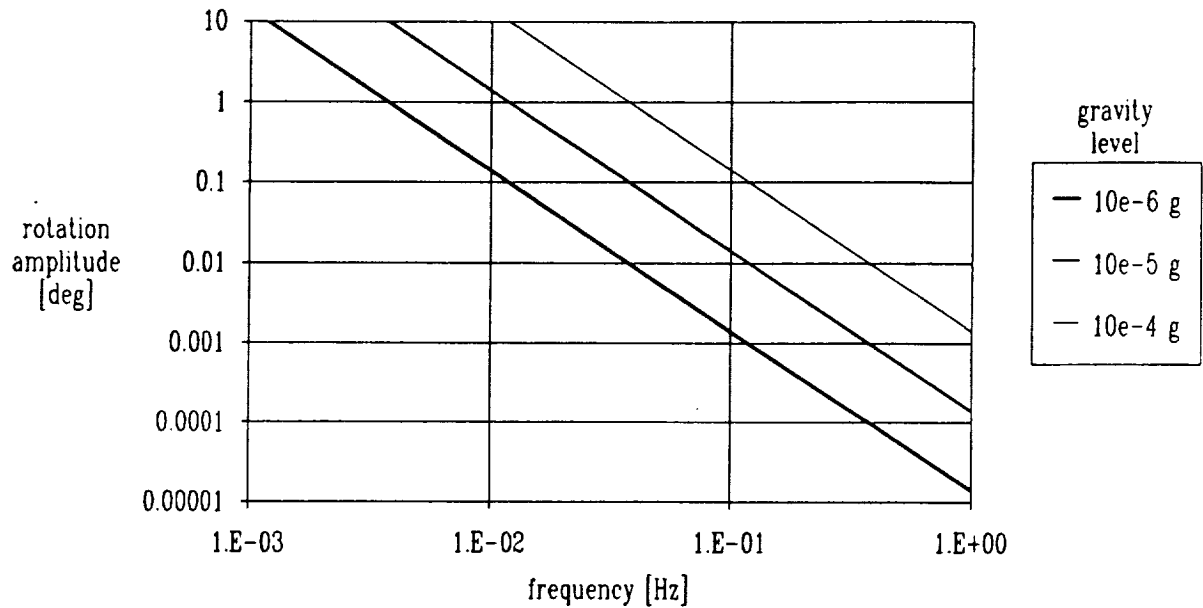


FIG. 4.4-13 MAX. ROTATION AMPLITUDE VERSUS FREQUENCY
FOR THREE LEVELS OF RESIDUAL GRAVITY

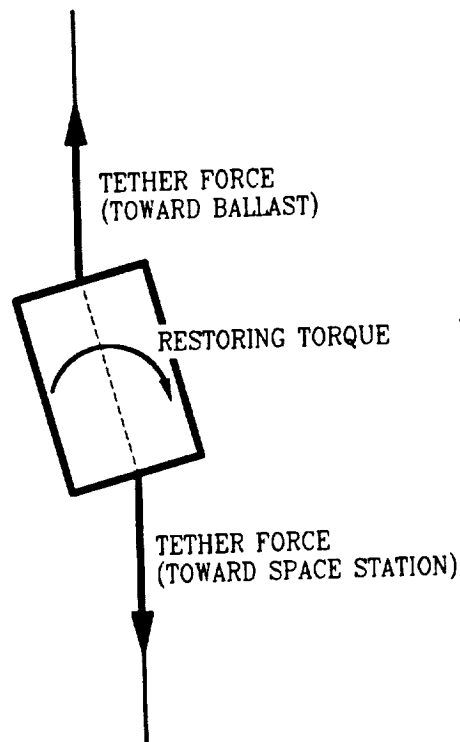


FIG. 4.4-14 TETHER GENERATED RESTORING TORQUE

if the Elevator is aligned with the reference frame no tether generated torque is present.

In case of pitch and/or roll motion the tension in the tether causes a restoring torque on the Elevator (see Fig.4.4-14).

The forces acting on the Elevator are given by:

$$F_b = 3 n^2 [M_b X_b + 1/2 \mu (X_b - X_e)^2]$$

$$F_e = 3 n^2 M_e X_e$$

$$F_s = F_e + F_b$$

with:

F_b = tether tension at the contact point between Elevator and tether toward the ballast

F_e = force acting on the Elevator itself

F_s = tether tension at the contact point between Elevator and tether toward the Space Station

M_b = ballast mass = 2200 Kg

M_e = Elevator mass = 2000 Kg

X_b = ballast distance from overall CG

X_e = Elevator distance from overall CG

μ = tether linear density = 0.1 Kg/m

In Fig.4.4-15a the stiffness of the Elevator relative to a torque acting around pitch is reported as a function of the desired gravity level. This stiffness increases slightly with increasing Elevator distance from CG as, although the tether tension in the portion between the ballast and Elevator decreases, the increase in the force acting on the Elevator is rather large (in effect proportional to the gravity level).

Around the yaw axis the elastic properties of the tether come into play supplying a restoring torque in response to attitude disturbances (tether tension cannot act around the tether axis if not through coupling effects between the motion around the principal axes of inertia).

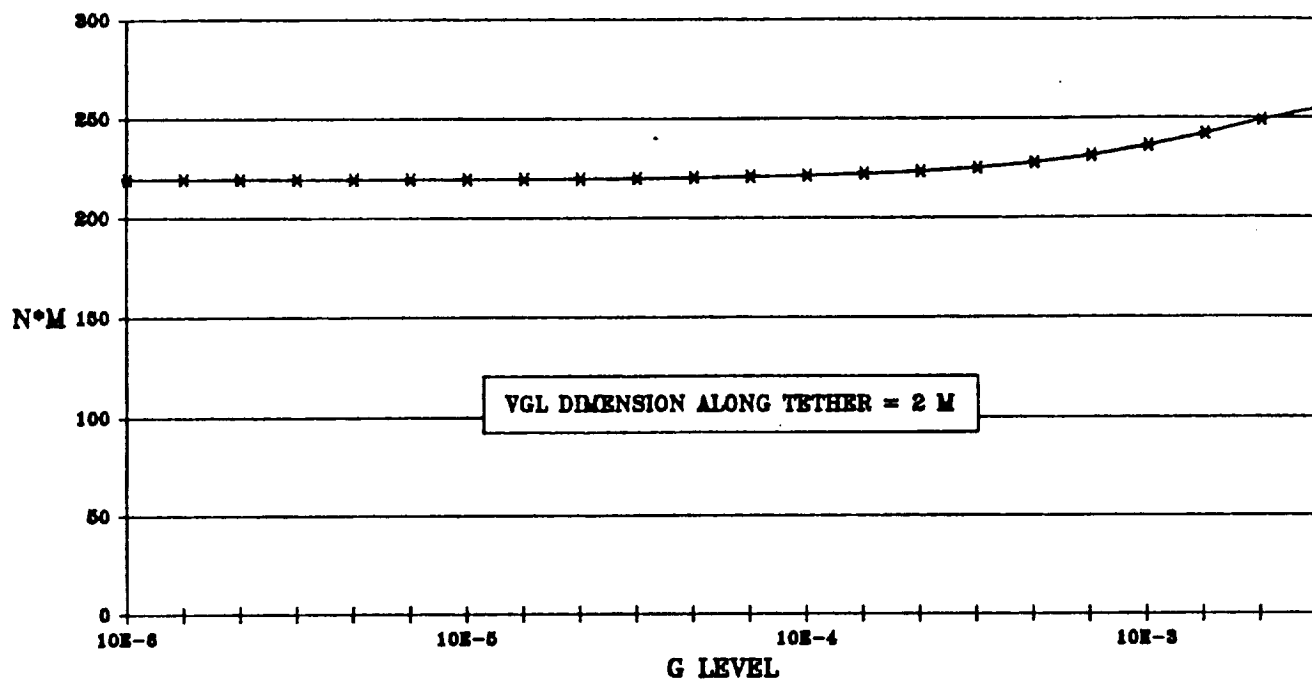


FIG. 4.4-15a PITCH STIFFNESS DUE TO TETHER TENSION

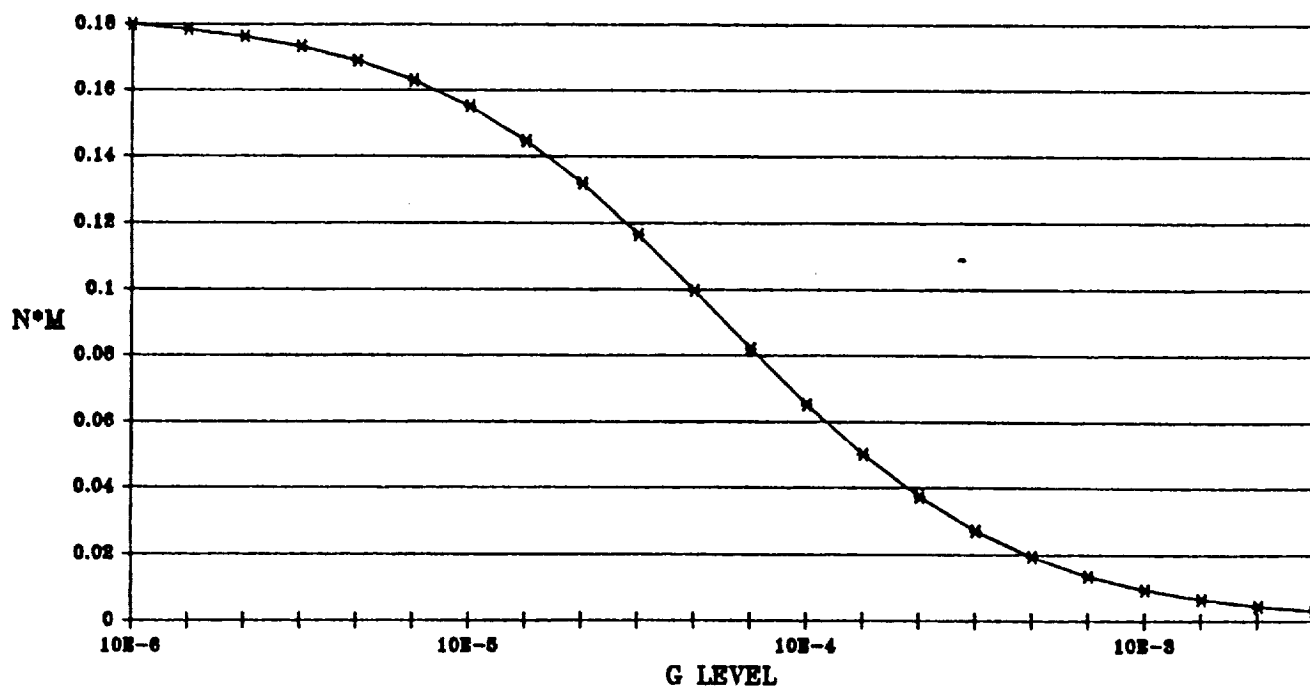


FIG. 4.4-15b TETHER TORSIONAL STIFFNESS

The torsional stiffness of the tether is given by:

$$K = G J_p / l$$

where:

G = transverse shear module = $26.3 \cdot 10^9$ Pa

J_p = polar moment of inertia of tether = $0.98 \cdot 10^{-9}$ m⁴

l = tether length between Elevator and Space Station.

The tether torsional stiffness is reported in Fig.4.4-15b as a function of the Elevator position. It can be seen that there are at least three order of magnitude between the stiffness around pitch/roll axes and the one around yaw. This is important as it means that motion around the pitch and roll axis is driven by tether tension whereas around yaw other effects and actions can be significant. Another important point to be underlined is the fact that Elevator attitude motion around the pitch and roll axes is coupled with linear motion along the roll and pitch axes respectively.

Environmental torques

If the Elevator is properly designed (that is with reasonable symmetry around yaw), the classic disturbances of aerodynamic drag and solar pressure should not be important. For instance if we assume that the center of aerodynamic pressure is 0.1 meter from the CG with an exposed surface of 1.5 m² the resultant yaw torque would be of the order of 10^{-4} N·m. The solar pressure effect is at least two order of magnitude lower.

It has to be noticed that the spring-like behavior of tether induced torques is particularly apt to control this kind of steady or quasi static disturbance torques, especially around the pitch and roll axes where the large stiffness of the system due to the tether tension can reduce the Elevator misalignment with reference to the reference frame to a negligible value.

Magnetic effects can be cancelled out with a proper design. Notice that the magnetic field is in any case distorted by the Space Station itself.

Transfer motion induced torques

The Elevator motion along the tether causes attitude motion of the Elevator around the pitch axis due to the Coriolis force and to the coupling between linear and angular displacements. This is not worrisome as long no experiments are performed during the Elevator motion. Residual vibrations could be a cause of concern which has been evaluated by the SAO simulations. On the basis of the SAO results we are confident that the tether tension restrains these motions within acceptable limits. In any case damping can be provided using proper actuators.

An important constraint has to be met, regarding the alignment of the principal axes of inertia with the roll and pitch axes. If this is not so, the coupling between the attitude axes, would cause motion around the yaw axis not easily controlled by the tether itself.

Docking torques

A special case of attitude control occurs when the Elevator is very near to the Space Station. In general it is necessary to rotate the Elevator around the yaw axis to reach the nominal docking position. At short length the cable torsional stiffness is quite high. For instance if the tether length is 1 meter and the required rotation is 5 degree a torque of 2.25 N m would be required. In effect the Elevator is not rigidly mated with the tether, but exchanges with it contact forces through friction. So the tether can react to torques on the Elevator only up to a certain value dictated by the friction. This is not necessarily a drawback as it could permit large yaw rotations of the Elevator with a small torque applied.

4.4.3.3 ADCS Equipment

Only a tentative description of the ADCS can be given at this stage.

4.4.3.3.1 ADCS Sensors

The reconstruction and control of the Elevator attitude requires continuous measurement by the ADCS sensors of the rotation angles and of the respective angular

velocities of the Elevator about pitch, roll and yaw (pitch, roll, and yaw axes constitute the natural frame to which the attitude motion of an Earth-pointing system, like the VGL one, has to be referred).

Measurement of roll and yaw angles (θ_x , θ_z) can be achieved by using a star sensor looking along the direction of the Y axis, nominally aligned with the pitch axis, and tracking a star close to orbital plane normal direction (see Fig.4.4-16).

The remaining pitch angle (θ_y) in principle could be determined by using either (A) a Sun sensor looking along the -Z axis or (B) two conical scanning Earth sensors mounted on the $\pm X$ sides of the Elevator.

(A) The angle ϕ between the Sun direction and the -Z axis, measured by the Sun sensor, depends on the Earth, Sun, Elevator relative position, and on the pitch and roll angles (see Fig.4.4-17). For small displacements ($< 3^\circ$) of the Elevator from the nominal attitude we get:

$$\cos \phi = \frac{(R_{11} x_0 + R_{21} y_0 + R_{31} z_0) - (R_{12} x_0 + R_{22} y_0 + R_{32} z_0) \theta_y - (R_{13} x_0 + R_{23} y_0 + R_{33} z_0) \theta_x}{1}$$

where:

x_0, y_0, z_0 = components of the unit vector pointing towards the sun direction in the Geocentric Equatorial Frame,

R_{11}, \dots, R_{33} = elements of the transformation matrix from the Elevator orbital frame (RSW) to the Geocentric Equatorial Frame.

The previous equation allows therefore to compute θ_y , once the sun ephemeris, the Elevator position on its orbit and the θ_x angle (measured by the star tracker) are known.

(B) The conical scanning Earth-sensor provides a direct measure of the angle 2β spanned by the chord joining the two points in which the scanning field of view (FOV) crosses the Earth edges. The values of β measured by the +X and -X sensor, and indicated respectively with β_1 and β_2 , depend on the pitch angle as follows (see Fig.4.4-18):

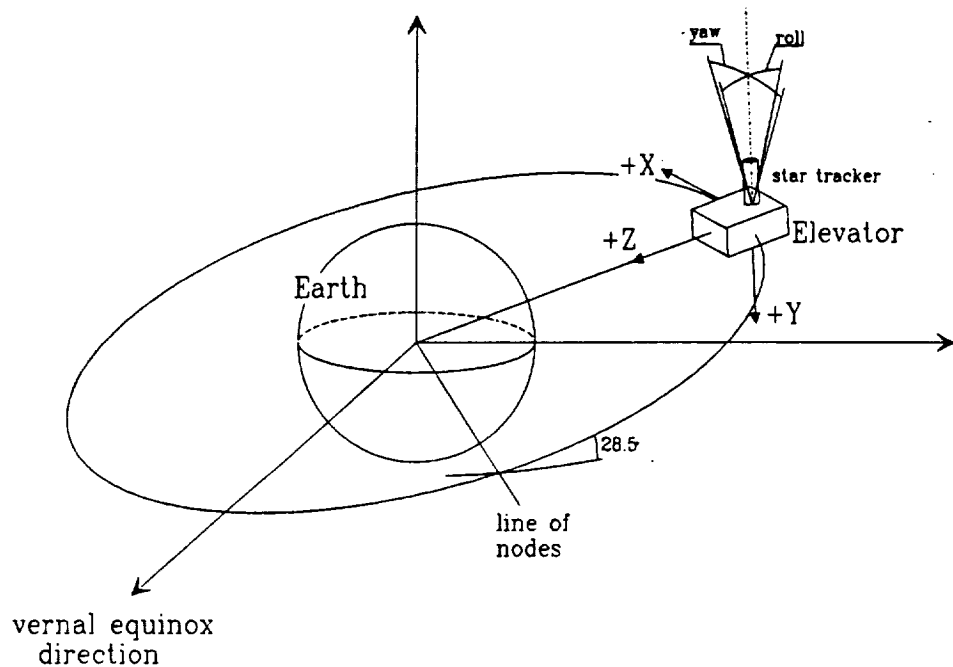


FIG. 4.4-16 MEASUREMENT OF THE ROLL-YAW ANGLES

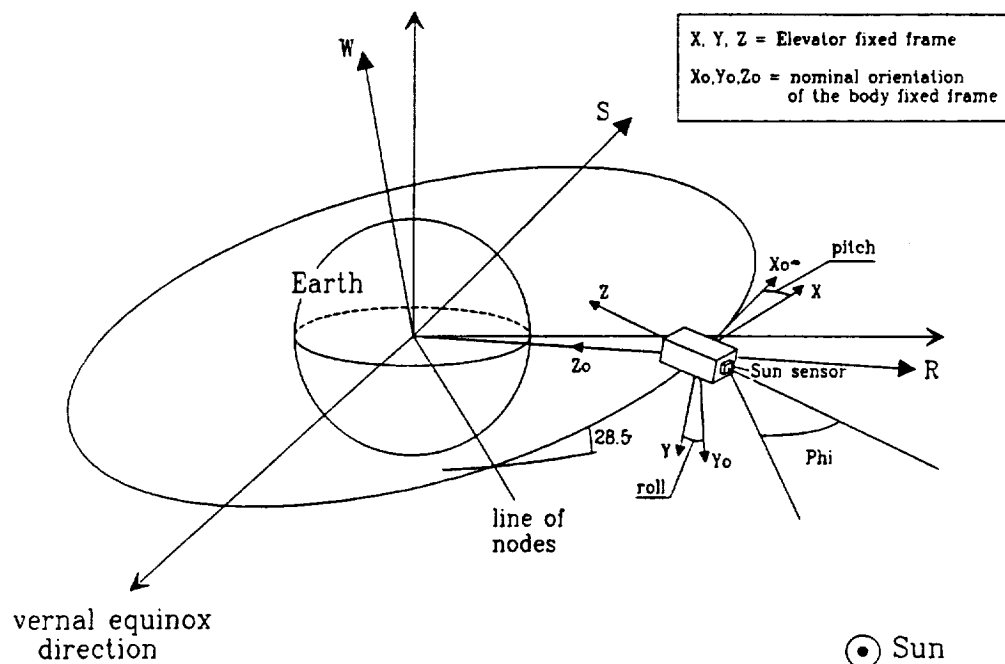


FIG. 4.4-17 MEASUREMENT OF THE PITCH ANGLE BY A SUN SENSOR

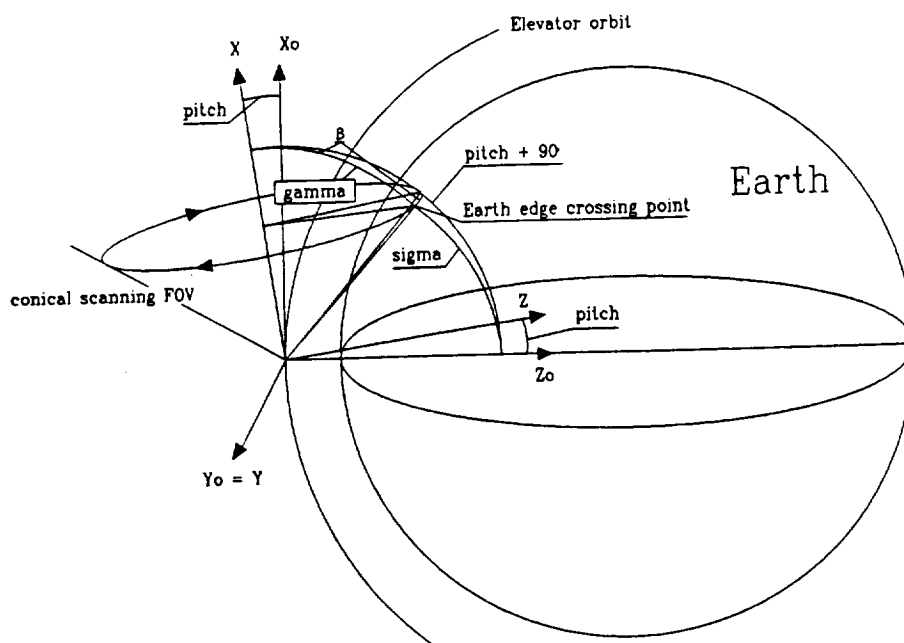
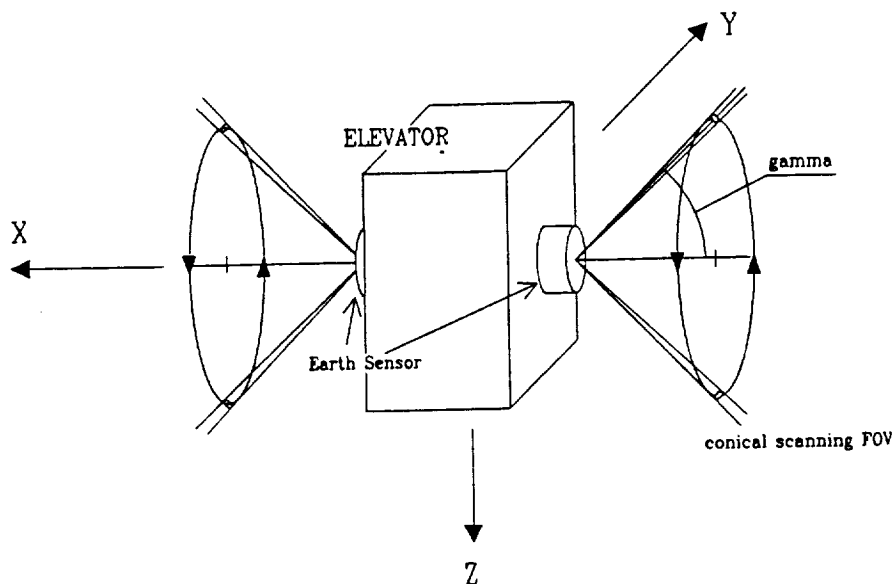


FIG. 4.4-18 MEASUREMENT OF THE PITCH ANGLE BY A CONICAL SCANNING EARTH SENSOR

$$\cos \beta_1 = \frac{\cos \sigma + \sin \theta_y \cos \tau}{\cos \theta_y \sin \tau} \quad (1)$$

$$\cos \beta_2 = \frac{\cos \sigma - \sin \theta_y \cos \tau}{\cos \theta_y \sin \tau} \quad (2)$$

where:

τ = scan conic angle of the sensor,

σ = angular Earth radius as seen by the Elevator.

By combining (1) and (2) we get:

$$\sin \theta_y = \pm \left[\frac{(\cos \beta_1 - \cos \beta_2)^2 \sin^2 \tau}{(\cos \beta_1 - \cos \beta_2)^2 \sin^2 \tau + 4 \cos^2 \tau} \right]^{1/2}$$

and $\theta_y > 0$ if $\beta_2 > \beta_1$, $\theta_y < 0$ if $\beta_1 > \beta_2$.

Note that the use of two Earth sensors mounted at 180° makes the pitch measurement independent from σ i.e. from the knowledge of the Elevator altitude.

The Earth sensors provide in principle a measure of the pitch angle all along the orbit, rather than the Sun sensor which allows to determine θ_y only when the Sun is in the sensor FOV. Nevertheless, the presence of the Space Station between the Earth and the Elevator could produce spurious signals in the Earth sensor detector when the scanning beam crosses the ISS itself.

By taking into account this drawback, together with the lower accuracy of the Earth sensor with respect to a fine Sun sensor (about 0.1° against 0.01°), it has been finally decided to select the latter for the measure of the third attitude angle of the Elevator.

The angular velocities, $d\theta_x/dt$, $d\theta_y/dt$, $d\theta_z/dt$, are instead obtained by means of three rate gyros.

The gyroscopes provide measurement of the Elevator angular rates, Ω_{mx} , Ω_{my} , Ω_{mz} , with respect to the inertial frame.

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The rates of the pitch, roll, and yaw angles are then obtained by the relation:

$$\Omega = \Omega_m - \Omega_r - d$$

where:

Ω = angular rate of the Elevator fixed frame w.r.to the reference frame (the pitch, roll, and yaw axes frame).

Ω is related to $d\theta_x/dt$, $d\theta_y/dt$, $d\theta_z/dt$.

Ω_m = Elevator inertial angular rate as measured by gyros

Ω_r = angular rate of the reference frame w.r.to the inertial frame

d = gyro drift

The gyro drift, which is the main source of error in the rate measurement, is estimated in the gyros updating process performed on the basis of the optical sensors data.

4.4.3.3.2 ADCS Actuators

The main problem on the ADCS equipment is the kind of actuators which should be used. In particular a problem is whether reaction wheels are needed or it is possible to use cold gas thrusters only (the use of hydrazine is not advisable to avoid problems with the gas plume impingement). At this point of the analysis it would be unwise to search a definitive solution. We point to the main issues which weigh on the choice of the attitude control actuators:

- a) For the control of the motion around the pitch and roll axes the reaction wheels are not deemed necessary, as well as the thrusters, as the degree of stabilization that the tether tension can supply seems sufficient. The damping of this motion could require active devices, but any attempt to counteract the tether tension generated torque would easily surpass the wheels and thrusters capacity (forces produced by cold gas thrusters are typically of the order of some hundredth of Newton). A passive oscillation damper, instead, seems a suitable device for reducing efficiently the rather quick

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oscillations around the pitch and roll axes. Notice that contrarily to ordinary satellite the Elevator has an intrinsic capability to damp momentum exchanging torques with the tether.

- b) Around the yaw axis the degree of stabilization offered by the tether is relatively low especially far away from the Space Station. An active system is deemed therefore necessary to counteract both the environmental torques and those induced by the coupling with pitch and roll motion.
- c) The reaction wheels offer the capability to control this motion in a very smooth manner as their action can be controlled in a continuous fashion (this point is particularly important for the very low g VGL mission phases), but they require in any case some device for the off-loading.
- d) Gas jets have a lower limit on the resolution of the torque and momentum that they can supply giving place to a limit cycle motion. Beside they also consume propellant, but as the Elevator is easily resupplied this is not a concern.

In substance a possible choice for the ADCS actuators, which seems according to the requirement of minimum perturbing acceleration produced by the control system, could be the following:

- Passive oscillation dampers acting around the pitch and roll axes with the tether tension playing the main role in the attitude control. Cold gas jets use is suggested if exceedingly high momentum damping requirement are foreseen (this can happen for instance at the end of large Elevator transfer motion).
- A reaction wheel for the attitude control around the yaw axis, with cold gas thrusters used only for the wheel off-loading. A passive damper could be helpful for fast oscillations reduction.

Of course, the definitive choice of the control philosophy requires extensive computer simulations of the attitude motion of the Elevator in all the foreseen nominal and emergency situations.

4.4.4 THERMAL CONTROL ISSUES

A meaningful thermal control definition typically requires a degree of detail and a "frozen" configuration which are available only in late stages of system design. What can be done at this very first level of analysis is more the underlining of the foreseeable problems and a review of possible solutions with their advantages and drawbacks.

The points which drive the Elevator thermal control subsystem analysis are, in brief:

- 1) Low earth orbit, with low inclination which implies a short duration thermal cycle, with the Elevator which can be alternatively in full Sun or completely in shadow.
- 2) The heat load from/to the payload is not known now, and in general it will change depending on the mission. It is evident that many variable-g experiments involving material phase change require a tight thermal control with large power requirement.
- 3) The microgravity condition which should be attained limits the amount of mechanical noise which can be accepted (active fluid loop system requiring a pump is a drawback).
- 4) The variable-g environment can have an impact on the performance of certain pieces of hardware. Here we are thinking to the heat pipes which, under the artificial gravity achieved on the Elevator, can change their ability to transfer heat (convection can either help or hinder heat transfer).

4.4.4.1 Assumptions

An initial set of assumptions has to be made just to start the discussion of the thermal control subsystem.

First of all a general idea of the shape and size of the Elevator is required.

To start the discussion a 1.5 m high and 1.5 m diameter cylinder can be used. The longitudinal axis of the cylinder is parallel to the tether direction.

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The assumed maximum heat load due to the payload and services is 400 W plus 100 W due to electrical loss in the batteries (80 % efficiency).

The minimum heat leak from the payload and services is 0 with still 100 W from the batteries. The idea in this case is that all the electrical power is used to heat experiments involving material phase change. If less power is required from the payload and equipments, more power is available to the thermal control.

A 200 W maximum power allocation to the thermal subsystem is assumed.

The range of acceptable temperature goes from 258 K to 313 K. This is to be understood as an average global value more useful as a reference than for calculation. In fact some components (notably batteries) have in general a more stringent requirement.

4.4.4.2 "ZERO ORDER" Thermal Analysis

The simplest possible thermal model of the Elevator can be made assuming that all the Elevator surfaces have the same value of emittance and absorptance.

For the hottest condition the Sun is assumed to be straight along the tether direction at the orbit noon (the worst case depends on the effective values of absorptance and emittance). See Fig.4.4-19.

The coldest condition takes place when the Elevator is in the Earth shadow.

Under these further assumptions we are able to calculate the effective areas and the impinging radiation (which is different from the radiative load due to the thermo-optical surface properties) involved in the thermal exchange.

Given that only the Earth generated heat is present when the Elevator is in shadow there is a ratio of almost 6 to 1 in the impinging radiation from full Sun view to Earth shadow.

The equations governing the thermal problem are:

$$\text{Input power} = J_s \alpha (A_s + a A_a) + J_t e A_e + P + P_b + P_t$$

$$\text{Output power} = \sigma e T^4 A_t$$

$$J_s = \text{Sun heat flux} = 1327 \text{ W/m}^2$$

$$J_t = \text{Earth heat flux} = 237 \text{ W/m}^2$$

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a = Earth albedo = 0.37

A_a = effective area for albedo = 3.72 m^2

A_s = effective area for Sun flux = 1.77 m^2

A_e = effective area for Earth flux = 3.66 m^2

A_t = overall geometrical area = 10.6 m^2

P = power input from equipments and payloads (0 in shadow, 400 W in Sun view)

P_b = power loss in batteries = 100 W

P_t = power available for thermal control = up to 200 W

T = equilibrium temperature (Kelvin)

For computing the "hot" case temperature a wide range of absorptance and emittance values has been swept (the fact that emittance and absorptance are not independent is neglected).

For computing the "cold" case temperature the same range of emittance values and a 0 to 200 W range of heaters power have been swept (absorptance is not a factor in this case).

The resulting temperatures for "hot" and "cold" cases are reported in Fig.4.4-20 respectively as solid and dotted line graphs.

It can be seen that no parameter combination can satisfy both the requirements for the highest and lowest temperature. Moreover from the graphs it can be deduced that the "hot" case is rather easy to deal with, whereas only with very low emittance the lowest temperature can be kept over the 258 K limit. This is not to say that passive thermal control is inadequate in any case, but merely that it is not the "natural" solution for the Elevator thermal design.

As a last point it can be noted that given the relatively short duration of the orbit the thermal capacity of the system has to be taken into account, thus limiting extreme temperatures.

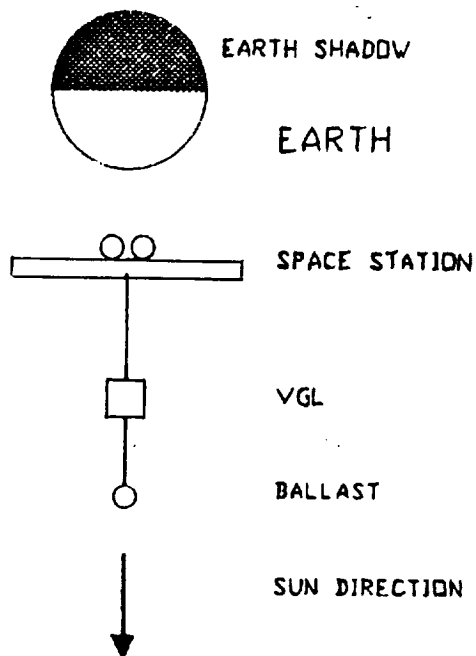


FIG. 4.4-19 HOT CASE ELEVATOR POSITION

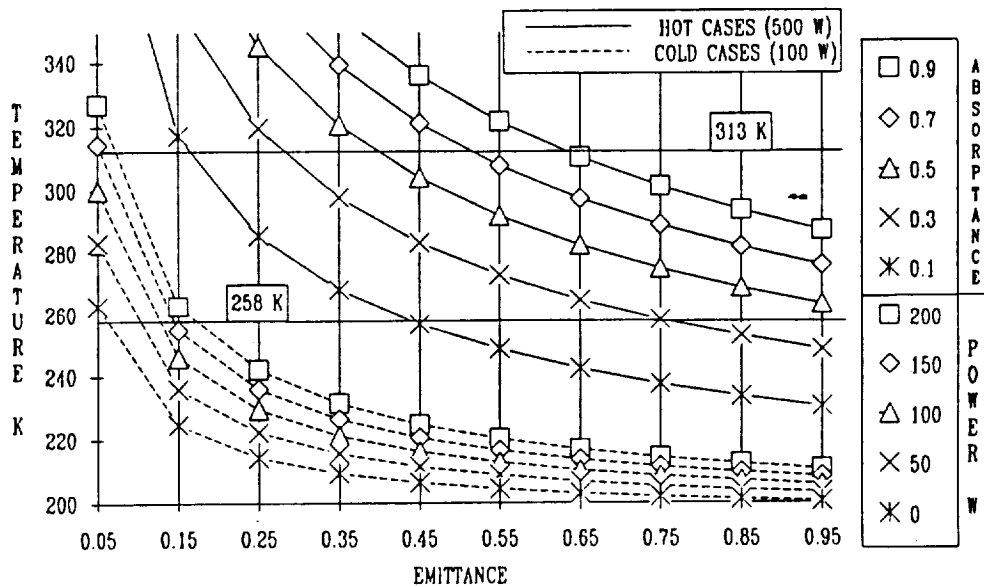


FIG. 4.4-20 ELEVATOR TEMPERATURE

4.4.4.3 Thermal Control Options

There are at least three thermal control options:

1) Purely passive system.

The realization of a purely passive control system (based upon the choice of appropriate combinations of emittance, absorptance of external surfaces, conductance, and heaters location) requires first of all an accurate knowledge of the internal heat distribution resulting from the radiation flux of the external environment and from the equipment power dissipation. Therefore such a system is critically dependent upon the payload characteristics, and would require a thorough redesign and reconfiguration as a result of payload modifications. In addition, it is very unlikely that the temperature excursion of high dissipating payloads or subsystems can be kept within adequate tolerances by a mere passive control.

2) Semi active system.

In this set we include all the systems involving heat pipes (both constant and variable conductance) and/or components which are able to change the radiative properties of external surfaces (shutters, louvers, etc.).

The advantage of these systems is that they offer a capability to deal with drastic changes in the heat load (due to a varying external environment or to equipments with a varying duty cycle) which is considerably greater than that of the purely passive systems.

Moreover the extremely high effective thermal conductance of the heat pipes makes these systems ideal for maintaining temperature control also of high dissipating components.

The main drawback is again the low flexibility resulting from the necessity of reconfiguring the array of pipes dedicated to the payload cooling every time its configuration or its thermal requirements are appreciably changed.

The reduced reliability of the system due to its increased complexity w.r.to a passive thermal control seems instead less decisive for a system like the VGL which can be checked out in space just prior to the mission start and that can be recovered in a matter of hours.

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3) Active system.

Here we mean those systems which include a cooling fluid loop activated by a pump. In general they offer the largest degree of flexibility which has to be traded off again with the complexity and, more to our point, with an unavoidable amount of mechanical noise. In the Elevator microgravity application this is a serious drawback even though low noise pumps are being developed just for this purpose.

At a first, conceptual level of trade off it appears that a semi passive system is the best choice for application in micro-g environment as it avoids the use of running machinery.

Of course, if the payloads to be mounted on the Elevator have configuration and thermal control requirements so different to impose a re-analysis and reconfiguration of the heat pipes for each mission, or the amount of heat to be disposed off is too large, then an active system, with careful location of the active mechanical components could become the preferable solution.

A purely passive system, instead, does not appear in any case consistent with the expected required performances.

This first glance at the thermal control problem is integrated with further details in the overall Elevator configuration analysis.

4.4.5 ACCELEROMETERS

Accelerometers are one of the key sensors for the VGL. During the station keeping of the Elevator along the tether, their main function regards the monitoring of the microgravity environment near the experiments in progress.

During the transfer phases from one g-level to another one (experiments switched off), the accelerometers are used for supporting the positioning operations of the Elevator at the height corresponding to the desired gravity level, and for controlling the damping of the motion-induced accelerations down to the value required for starting the experiments.

To date it is not foreseen to use accelerometers as sensors for an automatic feedback control of the longitudinal and transverse oscillations of the system, or of the Elevator attitude motion.

4.4.5.1 Accelerometers Requirements

The requirements on range, bandwidth, accuracy of the accelerometers which should be mounted on the Elevator are essentially dictated by the acceleration monitoring capabilities required by scientists (Ref. Section 3), and by the foreseen VGL microgravity environment.

The latter is characterized by acceleration ranging between about 1×10^{-8} and 4×10^{-3} g in amplitude, and from 0 to 100 Hz in frequency.

Acceleration sources at very low frequencies (0 - 0.01 Hz) are the gravity gradient, atmospheric drag, orbital perturbations, tether oscillations, and the VGL motion along the tether. The accelerations occurring in the band 1 - 100 Hz are caused by running machinery and by the motion of mechanical parts (valves, switches, etc.), while those in the intermediate range (0.01 - 1 Hz) are due to the Elevator attitude motion and, partially, to the tether oscillations induced by the crawling motion.

It follows that the required monitoring could be ensured by an accelerometers package having the following triaxial characteristics:

MEASUREMENT RANGE

- 10^{-2} g to + 10^{-2} g

FREQUENCY BAND

DC to 100 Hz

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MEASUREMENT ACCURACY 10^{-7} g from DC to 1 Hz, and not
exceeding a matched linear
increase with frequency, up to
100 Hz

Of course, these same accelerometers are suitable also for supporting the Elevator positioning along the tether at any desired micro-g level with the precision required by the experiments.

In order to be certain that the sensor is suitable for detecting the anticipated signal, its theoretical limit of resolution (or sensitivity), i.e. its intrinsic noise, must be lower than the smallest acceleration to be measured. In particular the sensor resolution is usually chosen to be an order of magnitude below the smallest signal at any given frequency; this, in our case, implies an internal noise with spectral density not greater than 10^{-9} g/√Hz in the frequency range 0 - 100 Hz.

In fact, if the instrument has the above mentioned noise, flat from 0 to 100 Hz, its resolution (rms noise power) on that bandwidth turns out to be:

$$\left[\int_0^{100} 10^{-18} df \right]^{1/2} = 10^{-8} \text{ g ,}$$

a value which is 10 times lower than the lowest signal (10^{-7} g) that should be measured by the accelerometer in the given frequency band.

The acquisition of high quality data during long periods of time, like the duration of the typical VGL mission (about 1 month), requires moreover that the accelerometers have good bias stability and low time-dependent drift and temperature coefficient of the bias.

The possibility of on-orbit calibration, a high degree of linearity in both the amplitude and frequency ranges, and a short thermal/mechanical stabilization time are also very desirable features.

During any mission of the VGL it is required, in addition, the knowledge of the frequency spectrum of the acceleration environment for the following reasons:

- to monitor the value of the (quasi-)steady component of the acceleration (generated by gravity gradient)

during the Elevator motion along the tether for its correct positioning to the desired micro-g level;

- to verify that the required profile of the residual acceleration as function of the frequency (Ref. Fig.3.3-1 of Section 3) has been maintained during the experiments activity.

The selected sensor(s) must therefore be interfaced with a Data Acquisition System and a Data Reduction System suitable to provide the required information about the signal spectrum; in particular the sampling rate must be at least twice the maximum frequency to be detected. In addition the information about the steady component of the spectrum should be available in real time as it has to be used to support the positioning operations.

4.4.5.2 Results of Preliminary Research About Accelerometers

A preliminary research has been performed aimed to collect documentation about the technical characteristics of existing accelerometers, to be used as a basis for a successive selection of sensors suitable for application on-board the Elevator. The accelerometers considered have been divided in two categories:

- 1) accelerometers currently available for space applications;
- 2) accelerometer under study or development, exploiting both conventional and new technologies.

Within the first category, the sensors whose characteristics (full-scale, bandwidth, resolution) keep close to the required ones are the MESA, the CACTUS, and the Q-flex.

The "MESA IMPROVED", the GRADIO, the Cavity Looking Accelerometer, and the solid state accelerometers, are instead the sensors belonging to the second class which seems the most promising for matching the required performances.

For a detailed description of the above mentioned accelerometers see the Quarterly Progress Report # 6.

Full-scale, frequency band, resolution of some of these sensors are reported in Figures 4.4-21 and 4.4-22,

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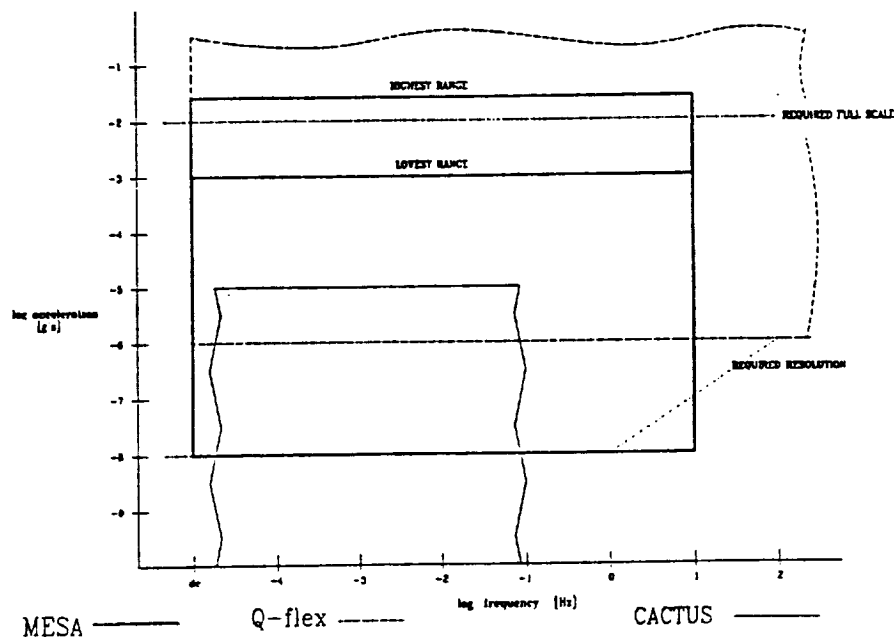


FIG. 4.4-21 FULL SCALE, BANDWIDTH, AND RESOLUTION OF THE ACCELEROMETERS CURRENTLY AVAILABLE.

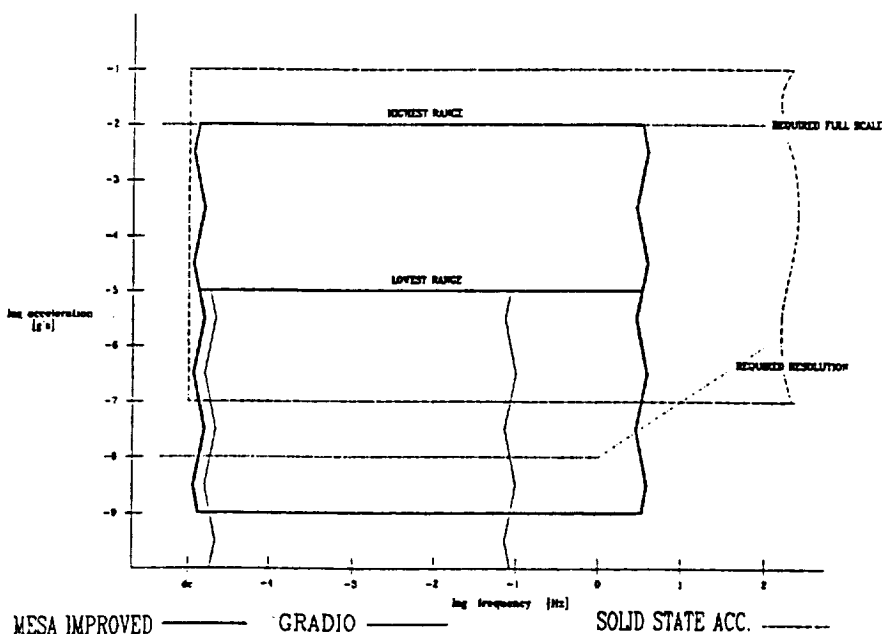


FIG. 4.4-22 FULL SCALE, BANDWIDTH, RESOLUTION OF THE ACCELEROMETERS UNDER DEVELOPMENT.

superimposed to the region of the acceleration-frequency plane defined by the required range, bandwidth, and resolution; vertical broken lines are used in those cases in which the sensor bandwidth is unknown.

4.4.5.3 Preliminary Conclusions

The principal advantage offered by the VGL is represented by the possibility of exposing the payload to different microgravity values. This represents also the principal difference with respect to the other microgravity missions, in which the experiments are always maintained at the same acceleration level. As a consequence, the monitoring of the microgravity environment on the VGL, as well as the operations of positioning of the Elevator itself along the tether, need the measure of accelerations characterized by a wide dynamic range.

By putting together this requirement with those on the measurement accuracy and frequency band, imposed by the scientists, we get a set of characteristics that are very difficult to find within a single state-of-the-art sensor.

In fact, in spite of the lack of the information about the CACTUS bandwidth, we can state that no one out of the currently available accelerometers considered, is able to fulfil all the requirements on range, frequency response, and sensitivity; the same conclusion applies also to the set of sensors including the MESA, the CACTUS, and the Q-flex together (in fact, it seems very unlikely that the CACTUS has a frequency band from 0 to 100 Hz).

At this point two possibilities exist:

- 1) make use of two or more sensors among those under development;
- 2) relax some requirements in such a way they can match the available accelerometer capabilities.

Again, a definitive answer about the feasibility of the first solution can be given only when complete set of data about the envisaged performances of the new sensors will be available by the accelerometer manufacturers.

If, instead, we want to make use of the available sensors it is necessary at least to give up detecting

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accelerations falling in the region (10^{-6} - 10^{-5} g, 10 - 100 Hz) of the acceleration-frequency plane. So doing, the requirement on accelerometer sensitivity can be raised by an order of magnitude in that bandwidth, and the resulting new set of requirements could be fulfilled by using the MESA and the temperature - controlled Q-flex together.

Nevertheless the comparison of full-scale, frequency response, resolution of the various sensors with those required for the VGL, alone it is not sufficient for giving definitive solution to the problem of the acceleration measurement. To this end other information are needed from the accelerometer manufacturers. In particular a precise knowledge of the behavior of the measurement errors as function of the amplitude of the input signal is essential for selecting an instrument that must detect accelerations with a dynamic range of at least 120 dB.

In view of these further information it will be possible to decide if the whole acceleration range can be covered by a single accelerometer (provided, for instance, with an autorange system), or if it is necessary to have recourse to more sensors each optimized for a more restricted dynamic range (wide, for instance, 40 or 60 dB).

Another factor which can drive the choice of the type and number of instruments is the precise determination in real time of the steady (or near-steady) components of the measured acceleration, required for supporting the positioning operations.

As the accurate detection of the steady-state or slowly varying accelerations within an accelerometer readout containing 10 or 100 Hz - frequency signals is still an unsolved problem, it could be necessary to split also the frequency band in intervals of smaller amplitude, to be covered by different sensors. By using, for instance, an accelerometer sensitive in the frequency regime 0 - 10^{-4} Hz, we can get from its output, and therefore in real time, the value of the gravity gradient acceleration inside the VGL, without performing additional analyses.

4.5

VGL PRELIMINARY DESIGN

The VGL (Variable Gravity Laboratory) is a facility to be mounted on the Space Station and designed to carry out microgravity experiments at different acceleration levels ranging from 10^{-6} g to 0.4×10^{-2} g.

The main element of the VGL is the Elevator, an object able to move in a controlled way along a tether deployed from the Space Station, on which is mounted the payload and all the subsystems required for running the experiments and collecting the scientific data.

The tether (10500 meters long) is attached to the ISS truss through a reel which allows the deployment and retrieval of the tether itself.

A 2200 Kg ballast is attached to the other end of the tether to keep it in tension during the various VGL mission phases.

A general view of the VGL system is shown in Fig.4.5-1.

A nominal VGL mission lasts between a week and one month, and consists of the following sequence of events:

- 1) The tether is deployed along the local vertical (upward).
- 2) The Elevator is hooked on the tether.
- 3) The Elevator is undocked from the ISS and the transfer maneuver along the tether is started.
- 4) By a suitable rotation about the tether axis the Elevator is brought from the docking attitude to the operational attitude.
- 5) The Elevator is positioned at the height corresponding to the desired gravity level and is kept in that position for the whole duration of the micro-g experiment(s). These operations are repeated throughout the mission as many times as required by the payload.
- 6) At the end of the experiments campaign the Elevator is brought back to the docking attitude and moved back to the ISS.
- 7) The Elevator is docked to the ISS and detached from the tether. The tether is retrieved.

Detailed description of the various elements which constitute the VGL is given in the following chapters.

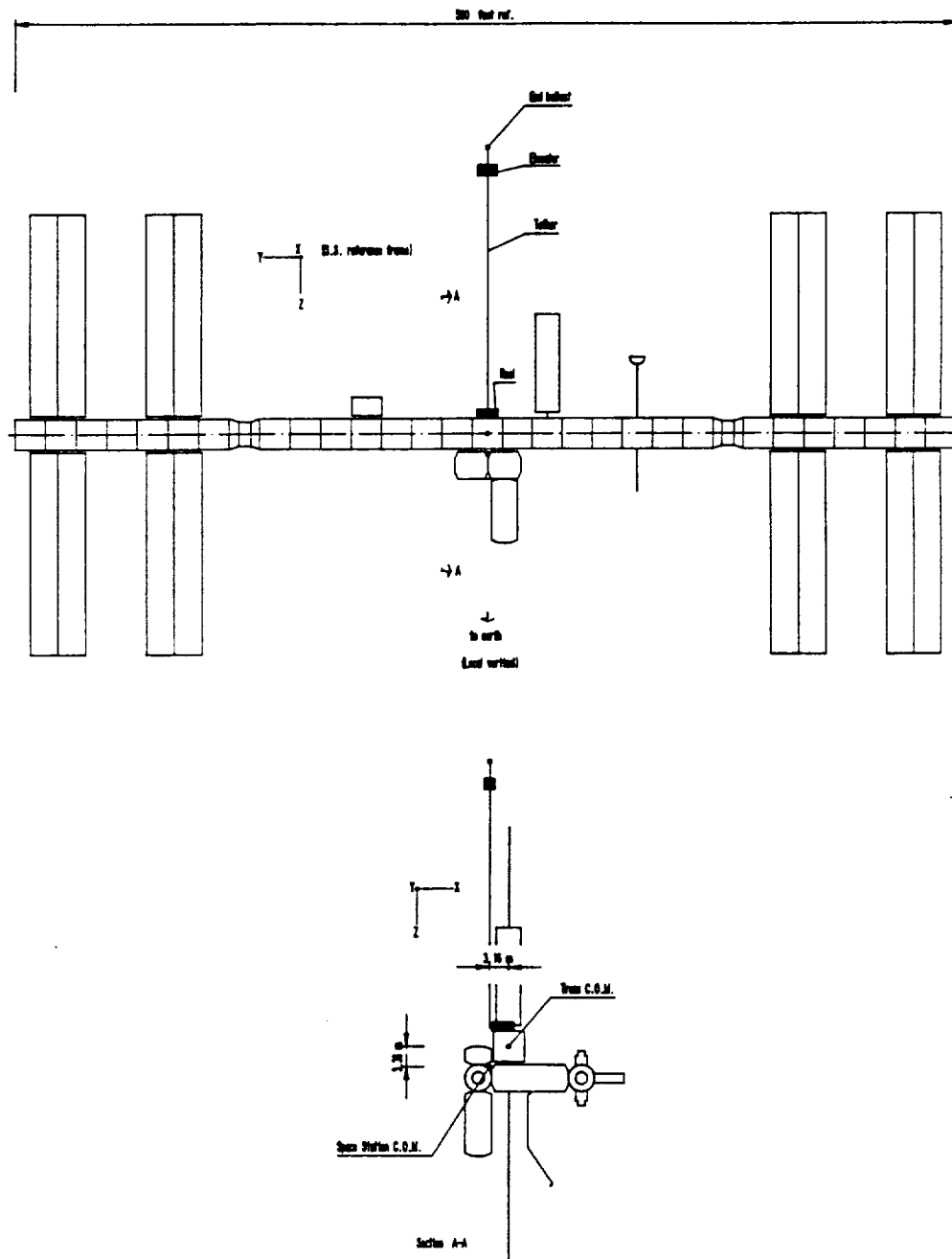


FIG. 4.5-1 VGL SYSTEM AND ITS ARRANGEMENT ON THE ISS

4.5.1 SPACE STATION INTERFACES

As the VGL is to be mounted on the ISS, we have to avoid undesired torques at the latter and hence the tether, when deployed, must go through the CG of the ISS. This constraint limits the choice of the tether/ISS attachment point to two solutions. The first one is to joint the tether to the ISS truss through its center of gravity on the side opposite the Earth while the second one is to joint the tether on the side looking towards the Earth. The interface has been located outside the truss envelope to simplify the mounting avoiding at the same time interference with other ISS activities. The following considerations drive the choice of the first solution:

- a) hazardous interaction in the modules area is avoided.
- b) interference with the Space Transportation System (STS) flight path is avoided even if it is assumed that the tether is not deployed during STS maneuvers.

Figure 4.5-1 graphically summarizes these assumptions showing the overall arrangement relevant to the phase-1 ISS configuration.

From this Figure we see that the deployed tether axis passes through the ISS CG (see Ref.[7]) and the VGL system is located opposite the modules area.

Note that the reduced ballast size comes from the theoretical assumption of the use of a compact homogeneous cube of high density material (mass dens.=17000 kg/cu.m.). The reel interfaces the ISS by means of a dedicated "sliding table" whose task is to slightly displace the tether attachment point (in the XY plane of the ISS reference frame) in the case of ISS CM location changes. In our conceptual design a displacement of ± 50 mm in both axes has been assumed as higher displacement that can be counteracted.

The reel envelope is positioned in such a way to reduce the obstacle around the ISS.

In Figures 4.5-2 through 4.5-4 orthogonal projections of the VGL assembly and its geometrical interfaces toward the ISS are shown. Clearly the proposed VGL/ISS interfaces have to be verified in detail according to the present/future ISS requirements.

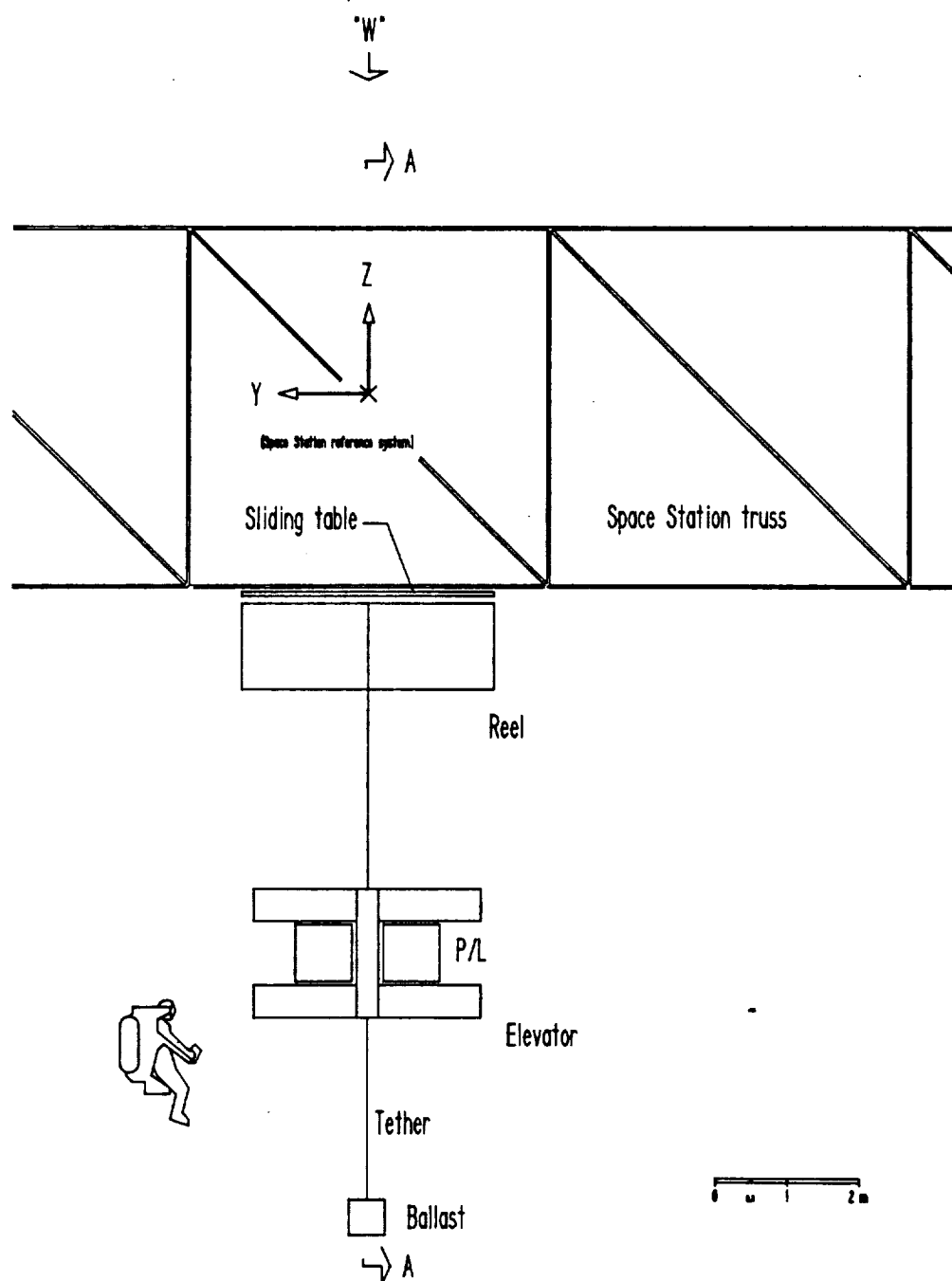


FIG. 4.5-2

VGL ASSEMBLY (Y-Z VIEW)

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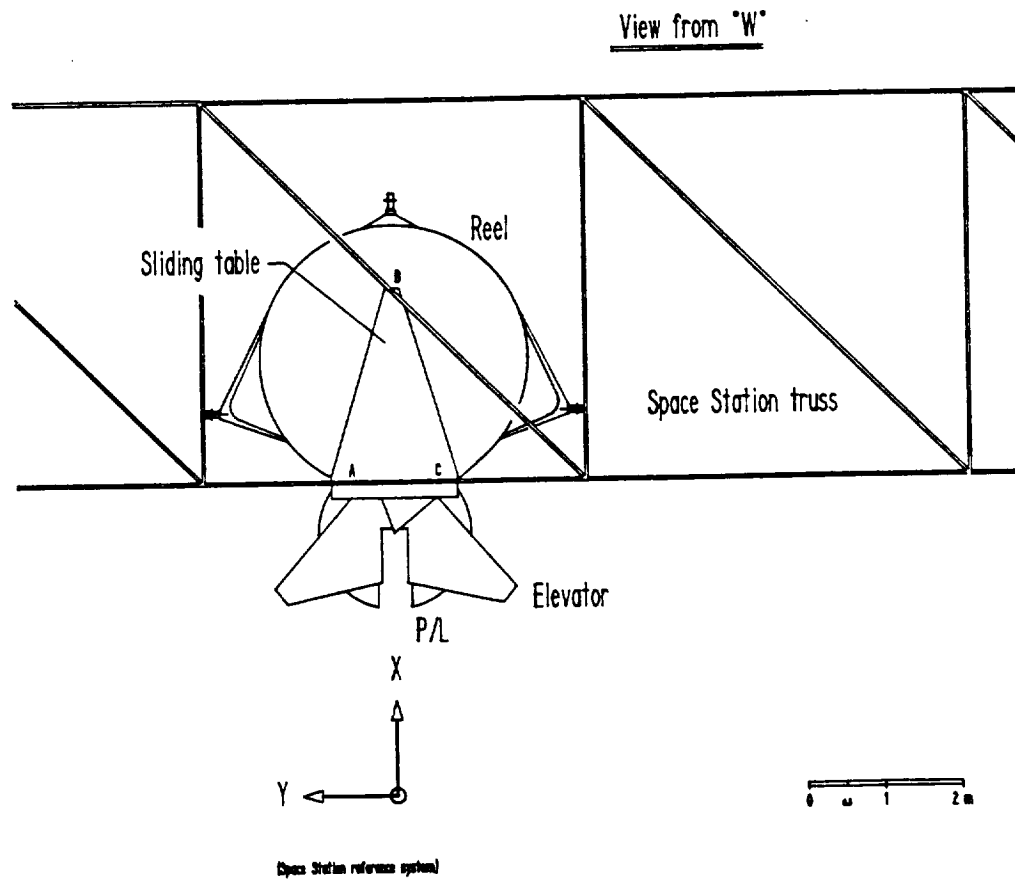


FIG. 4.5-3 VGL ASSEMBLY (X-Y VIEW)

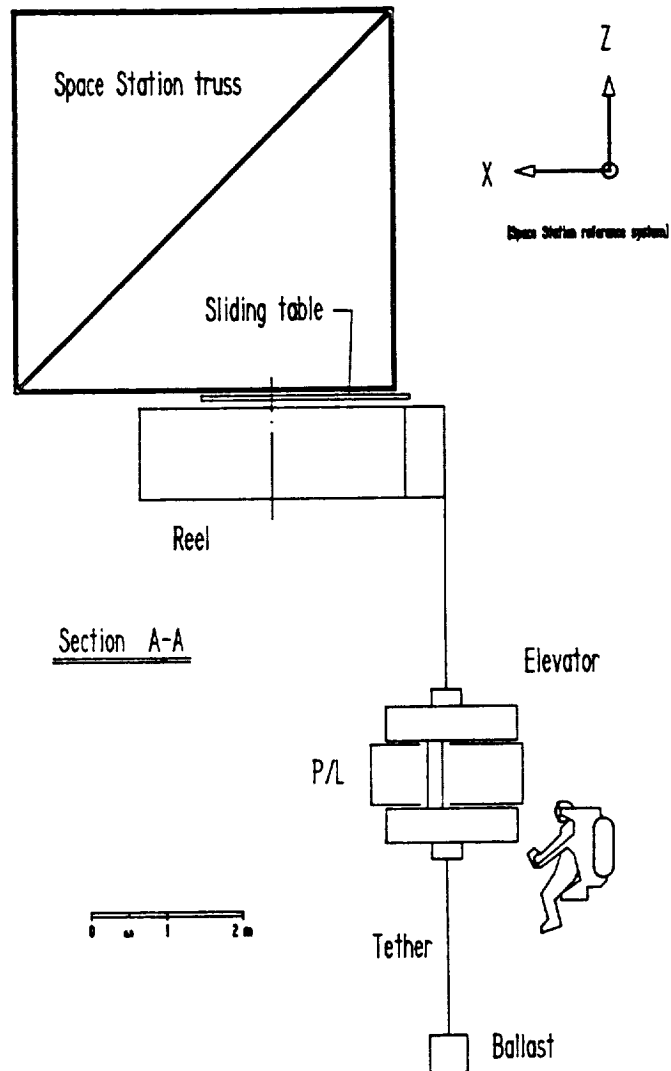


FIG. 4.5-4

VGL ASSEMBLY (X-Z VIEW)

The sliding table must be considered as a first approach to the VGL/ISS mechanical interface and can be subjected to further improvements.
In the following paragraphs a brief description of the reeling system and sliding table is given.

4.5.1.1 Sliding Table Description

Conceptually the sliding table is composed of a flat triangular plate joined to the ISS truss (points A,B,C in Figure 4.5-3) on one side and supporting a double cross sliding system on the other side.

Figure 4.5-5 shows the assembly from the reel location point of view, while Figures 4.5-6 through 4.5-9 show some details.

The sliding system is obtained by means of two flat triangular shaped trusses, each driven by a redounded linear actuator.

The external truss interfaces the rigid plate by means of suitable guides allowing $\pm X$ axis D.O.F. (ISS ref. frame) while the internal truss interfaces the external one in the same way allowing $\pm Y$ axis D.O.F.; finally the internal truss is provided of interfaces toward the reeling system.

The proposed solution seems to be compatible with the minimum constraints required, assuring at the same time a very compact design; anyhow deeper analyses are requested to fully strengthen this solution.

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SLIDING TABLE ASSEMBLY

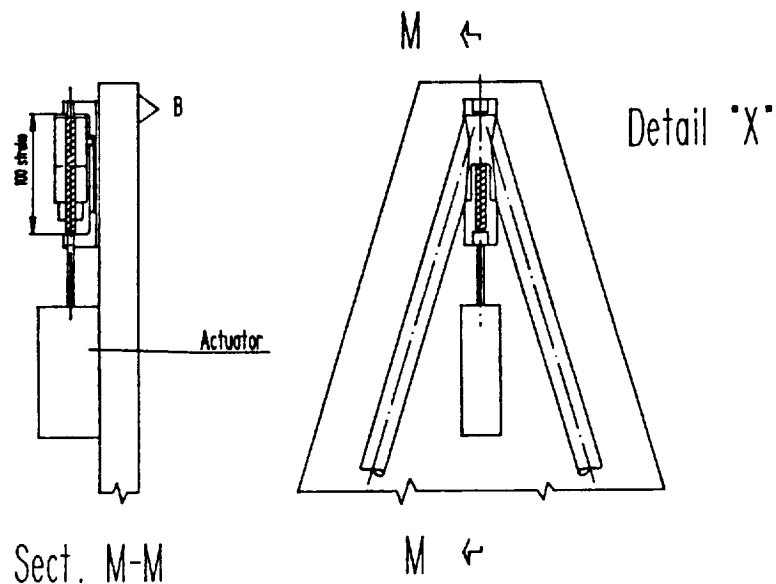


FIG. 4.5-6 SLIDING TABLE (DETAIL X)

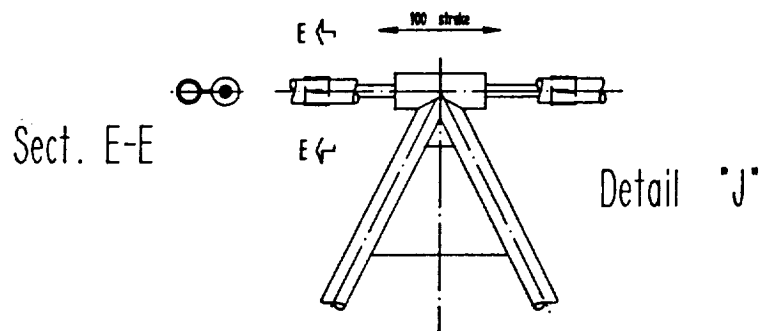


FIG. 4.5-7 SLIDING TABLE (DETAIL J)

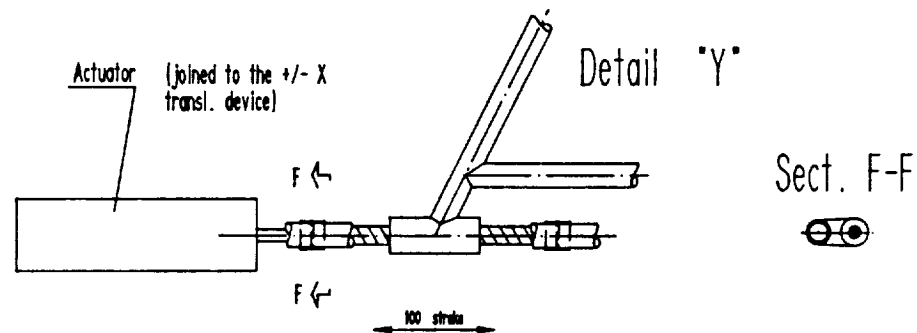


FIG. 4.5-8 SLIDING TABLE (DETAIL Y)

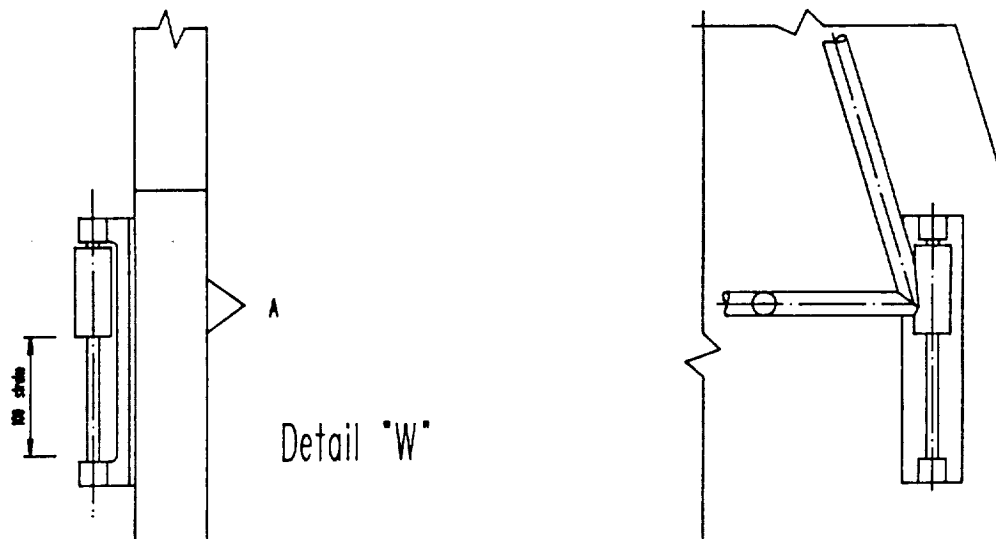


FIG. 4.5-9 SLIDING TABLE (DETAIL W)

4.5.1.2 Reeling System Description

The reeling system is, apart from the several external interfaces, a cylinder 3.5 m in diameter and 1.2 m in height.

It has the main task to actuate and control the tether deployment and retrieval; moreover it allows the interface toward the Elevator when the latter is not on the tether (parking position).

Figure 4.5-10 shows the reeling system assembly while Figure 4.5-11 shows the Elevator parking position and the relative stroke to be tether mounted. Only a conceptual scheme of the reeling system has been given as the correct allocation of the several measuring and actuating devices requires deeper configuration analyses not involved in this working phase.

The "drum" on which the tether is wound has its shaft mounted cantilevered on the circular plate facing the ISS; it is tentatively sized (as the real tether characteristics are, at this time, not well defined) to contain a 11000 m tether length on a 3 m diameter and 1m width cylinder.

Clearly the drum diameter is to be sized to avoid undue tether material stresses and the following equation can be used for a preliminary verification:

$$\text{PHI} = (\text{Smax}/\text{Eeq}) \cdot (\text{L}/\text{r})$$

being:

PHI	= allowable winding angle	
Smax	= max desirable tether stress	[100 MPa]
Eeq	= equivalent Young module of the tether	[30 GPa]
L	= tether length	[10500 m]
r	= tether radius	[0.005 m]
R	= drum radius	

Obviously it has to be $L = \text{PHI} \cdot R$

From the calculation it turns out to be $R = 1.5$ m and $\text{PHI} = 7000$ rad; the reel drum turns about 1200 times to completely retrieve the tether in about 12 "layers".

Assuming a minimum drum diameter of 3 meters, a tether diameter of 10 mm, and a coil interspace of .5 mm the diameter of the drum plus tether layers is approx 3.22 m (3.46 m if the tether diameter is 15 mm).

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The reeling system equipment is housed inside the drum free volume, and is attached to the internal side of the top (-Z) circular plate.

This plate is however made up of a fixed structural strip on which are hinged two semicircular plates (doors) sustaining the equipment.

The doors allow an easy internal inspection and/or equipment substitution as they rotate 90 degrees each, once the Elevator is shifted away.

A truss is connected to the structural strip, on truss vertex a rail drives (by means of a suitable docking interface) the Elevator on the tether.

Points E,F,G give the location of the reeling system/sliding table interface.

Because of the reeling system positioning with regard to the ISS, the tether must rotate of 90 degrees to be parallel to the drum axis; this involves the use of a radial path not lower than the drum one to avoid high tether material stress.

This could be done by means of a "circular arch" hinged to the nominal tether release point (point "T" of the reeling system cylinder prominence) and tilting from point "1" to point "2", as shown in Figure 4.5-10, to wind up/unwind the tether on the drum.

The circular arch can be imagined as a number of little pulleys mounted on it.

Dedicated studies should be performed in the future to globally design the reeling system including the measurement devices and actuators.

Being the tether release point fixed with respect to the rail end point "m", the mounting of the Elevator on the tether is greatly improved.

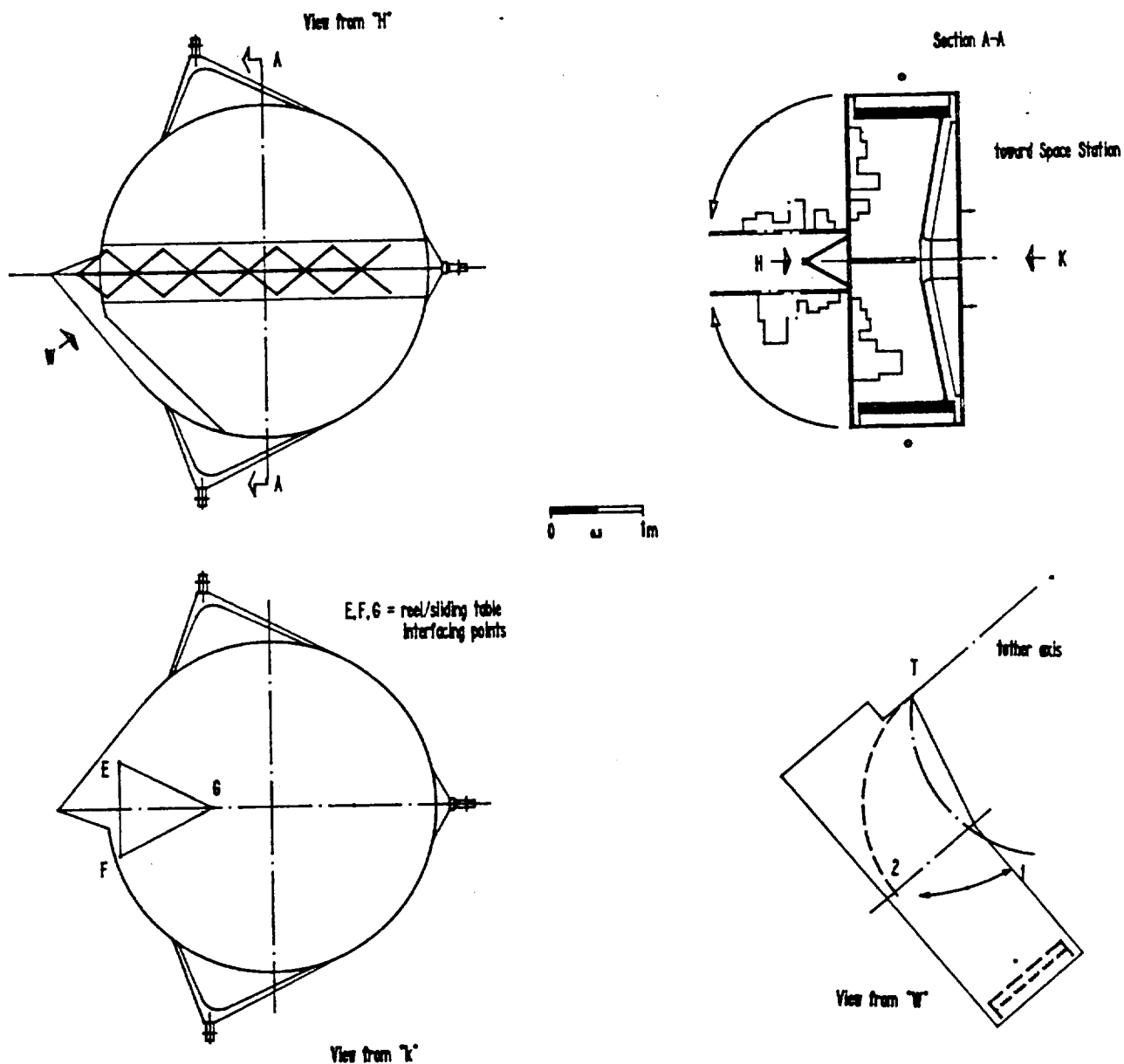


FIG. 4.5-10

REELING SYSTEM ASSEMBLY

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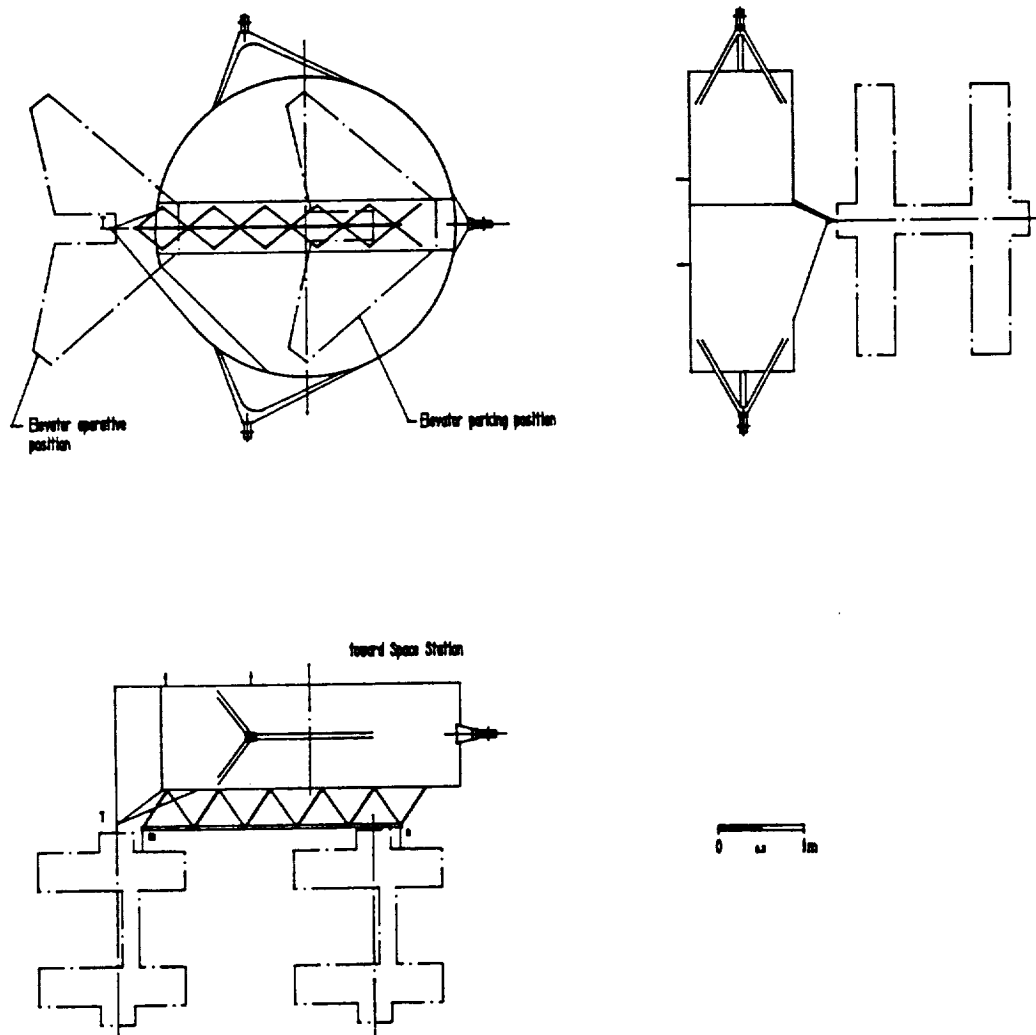


FIG. 4.5-11

REELING SYSTEM/ELEVATOR INTERFACES

4.5.2 ELEVATOR CONFIGURATION

4.5.2.1 Configuration Selection

Basic requirements on the Elevator configuration are :

- o possibility of Elevator hooking on the tether in a way allowing the tether to pass through the Elevator CM, and simple attachment and detachment operations.
- o accommodation as near as possible to the Elevator CM of payloads with very different characteristics.
- o easy payload replacement.
- o location of body-mounted solar arrays such as to have a good illumination of the solar cells for every position of the Sun and orientation of the orbit.
- o provision of a deep-space-looking surface for radiators and star tracker accommodation.
- o accommodation of Elevator subsystems such as large primary batteries, etc.
- o easy subsystems access, replacement and refurbishment
- o Space Shuttle payloads compartment compatibility.
- o accommodation of the docking interface.

As a result of the preliminary system study performed, it has been selected a configuration in which a slot allows the Elevator hooking on the tether up to its CM. Moreover the Elevator is split in two modules:

- the Service Module, the "fixed part" of the Elevator, accommodates the subsystems and is substantially the same for all the missions.
- the Payload Module, detachable from the Elevator, houses the micro-g experiments and, apart from the standard mechanical and electrical interfaces with the Service Module, can have different configurations in function of the payload characteristics.

The Service Module is, in turn, made up by two separated V-shaped modules, connected by a beam, each of them accommodates about half of the mass of all subsystems.

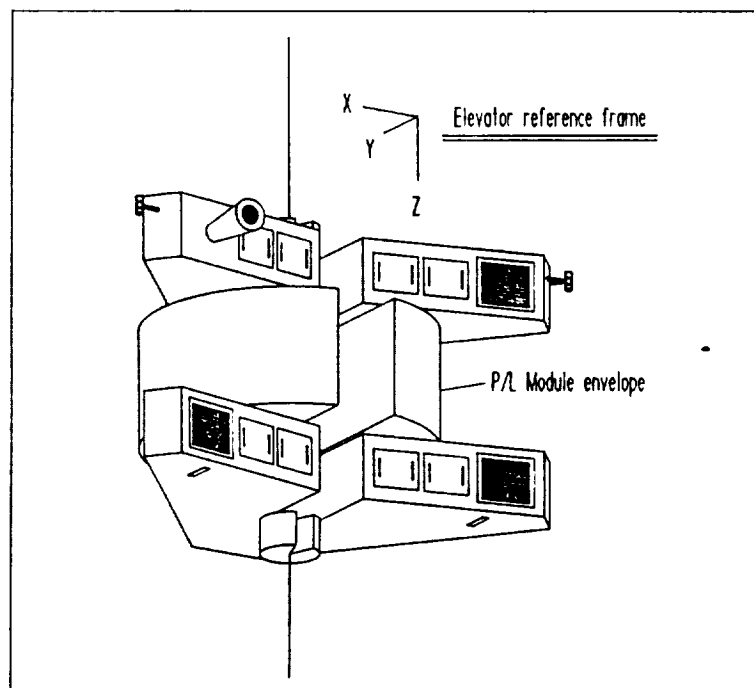
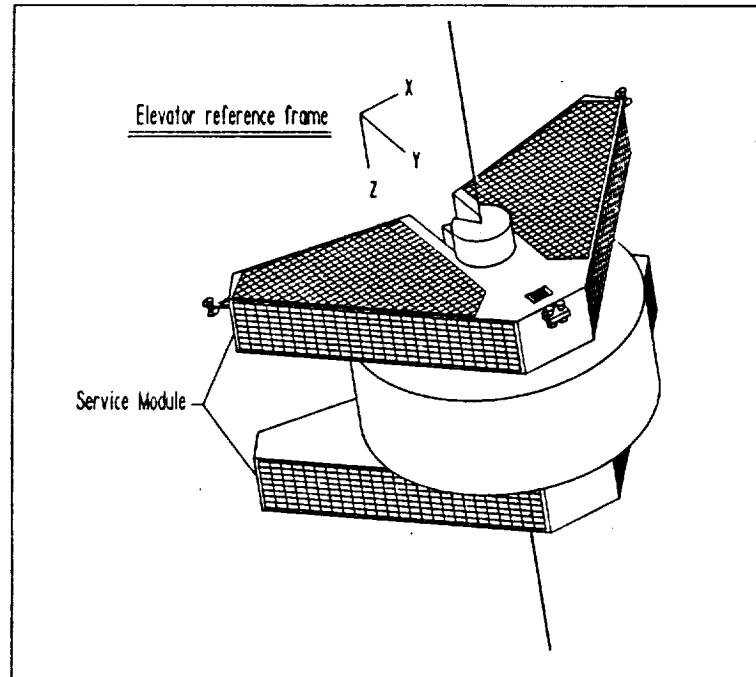


FIG. 4.5-12 ELEVATOR OPERATIVE CONFIGURATION (AXONOMETRIC VIEW)

The Payload Module is mounted between these two platforms. So doing, the Elevator CM is always near the payload, whatever it is the mass of the payload itself. Of course, both Service and Payload Modules are provided with a slot for the tether insertion.

The operative ("on-tether") Elevator configuration is shown in Fig.4.5-12, together with the Elevator reference frame defined as follows:

Z-axis: along the tether axis, positive towards the Space Station.

Y-axis: perpendicular to the Z-axis, in the Elevator symmetry plane containing the Z-axis, positive entering in the slot.

X-axis: completes a right-handed orthogonal triad.

The origin of the reference frame is located in the CM of the Elevator.

The docking/undocking attitude of the Elevator is determined by the position of the ISS interfaces and is shown in Fig.4.5-13.

The flight attitude, instead, comes from the requirement of having a good illumination of the solar panels, and a side of the Elevator always in shadow.

As a result of the analysis of the solar illumination of the VGL (Ref. Quarterly Progress Report # 7) the following decisions were taken:

- the solar arrays (about 5.6 m²) are placed on the $\pm X$ sides (the slanting sides) and -Z side of the Service Module.
- the Elevator should flight keeping one of the two attitudes so defined (see also Fig.4.5-14):
 - (1) X, Y, Z-axis along roll, pitch, and yaw.
 - (2) X, Y, Z-axis along -roll, -pitch, and yaw.

The choice of the particular flight attitude depends on the position of the Sun (i.e. on the day of the year), and the orbit orientation (i.e. the longitude of the ascending node). Figures 4.5-15a/b show the effective (perpendicular illuminated) solar panel area available in function of the year's day and of the node longitude, for the given cells location and for both the flight attitudes.

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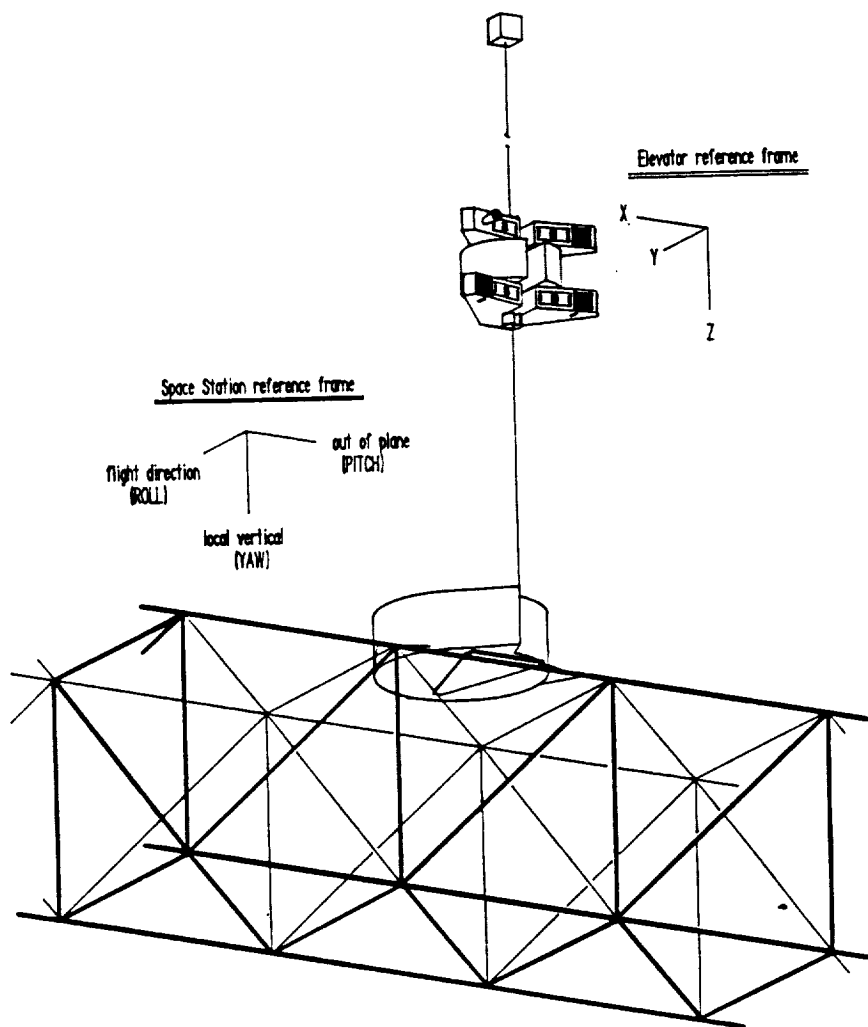


FIG. 4.5-13 ELEVATOR DOCKING/UNDocking ATTITUDE

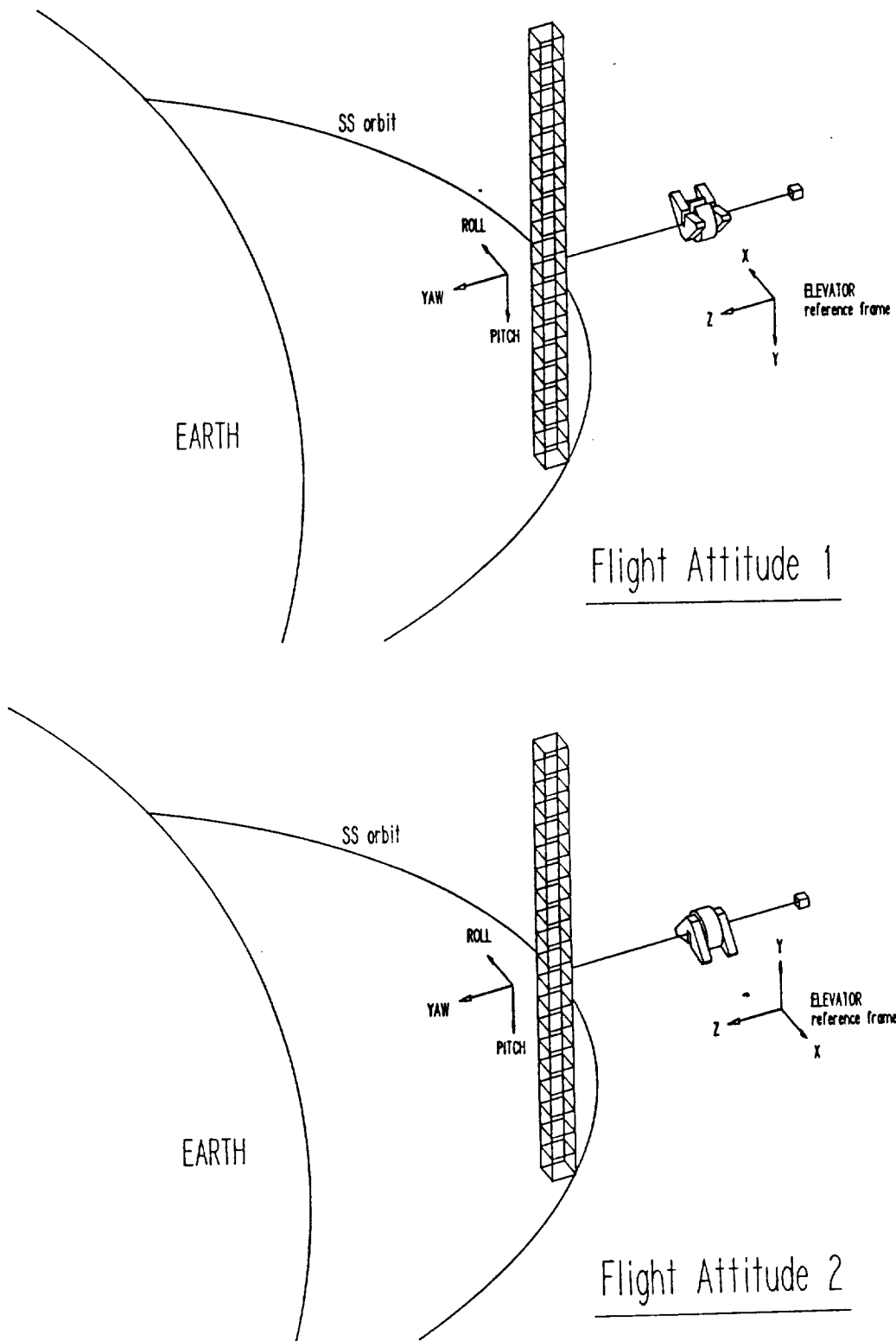


FIG. 4.5-14 ELEVATOR FLIGHT ATTITUDES

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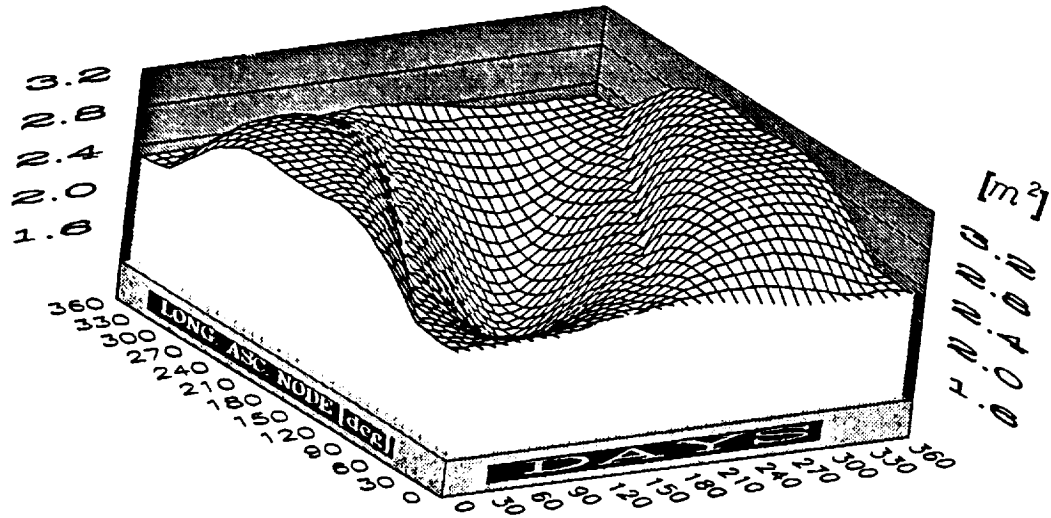


FIG 4.5-15a EFFECTIVE SOLAR PANEL AREA IN ATTITUDE (1)

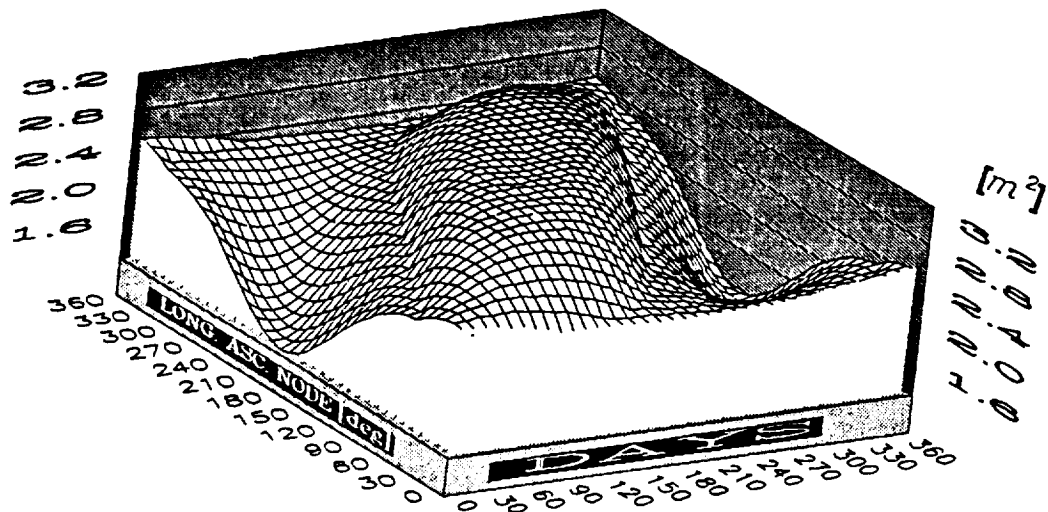


FIG 4.5-15b EFFECTIVE SOLAR PANEL AREA IN ATTITUDE (2)

The result is that, in every condition, it is always possible to obtain from 2 to 3 m² of effective area by orientating the Elevator frame in one of the two ways described. In addition, so doing, the -Y side of the Elevator never receives direct sunshine. Note that the flight attitudes are achieved starting from the docking/undocking one through $\pm 90^\circ$ rotation about the Z-axis.

4.5.2.2 Service Module Layout

The main features of the Service Module (SM) are as follows (see Fig. 4.5-16 through 4.5-20).

- a. The SM consists of two V-shaped modules mounted on a beam at a relative distance of 0.9 m. The volume available for equipment accommodation inside each module is about 0.9 m³. A slot in between the modules allows the tether to be inserted.
- b. The mechanisms for the hooking of the Elevator on the tether and for the actuation of the motion are placed externally at the top and bottom of the SM.
- c. Four 0.8 m² and two 1.2 m² solar panels are mounted respectively on the \pm X and -Z sides, while the -Y side accommodates the radiators for heat rejection.
- d. The +Z module of the SM ("Lower Module") houses the Data Handling, Telecommunication, and the Power Distribution and Control equipments. Two microstrip antennas are located on the +Z surface of this module, so as to irradiate always towards the Space Station.
- e. The -Z module ("Upper Module") houses the whole Attitude Determination and Control Subsystem. The star tracker protrudes from the -Y side, while the sun sensor is located on the -Z surface. Three sets, four thrusters each, are placed at the "vertices" of the platform.
- f. Primary batteries are equally shared between the two modules, and are inserted into the modules through openings in the -Y side. This arrangement allows easy and quick replacement of the batteries themselves.
- g. The accelerometer package is located on the beam which connects the two modules at the same height of the Elevator CM.
- h. Two keel fittings, used for fixing the SM inside the Shuttle cargo bay, are mounted on the +Y side.

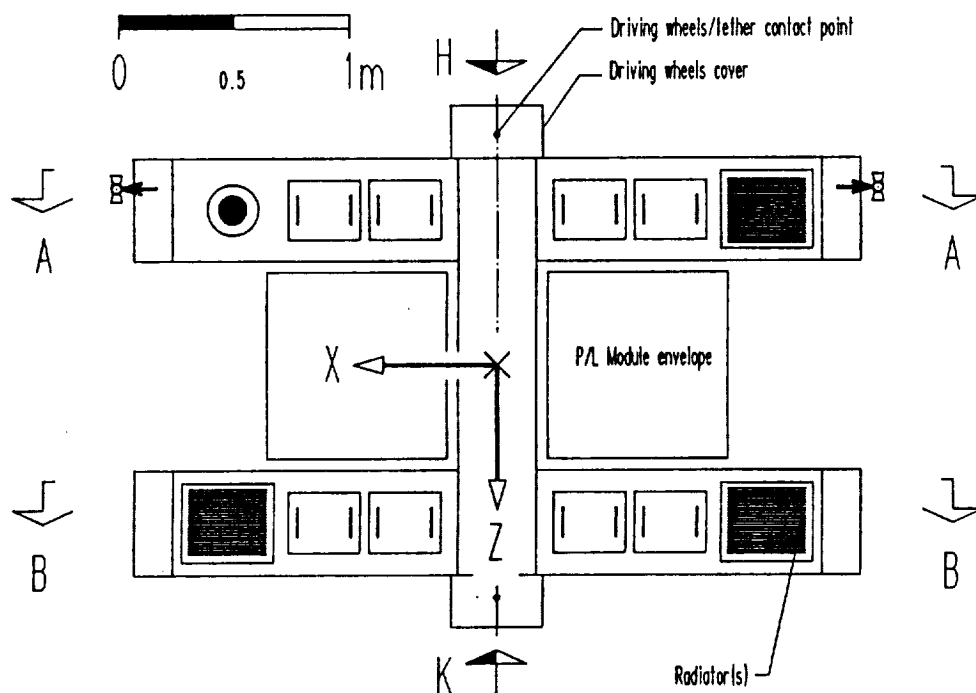
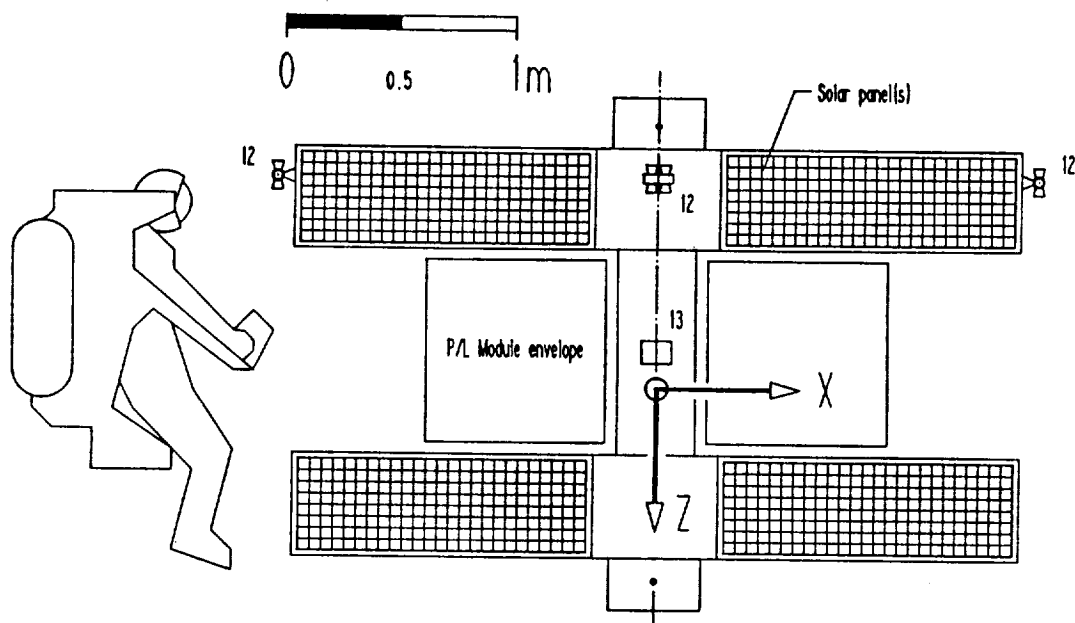


FIG. 4.5-16 SERVICE MODULE - FRONT AND BACK VIEWS

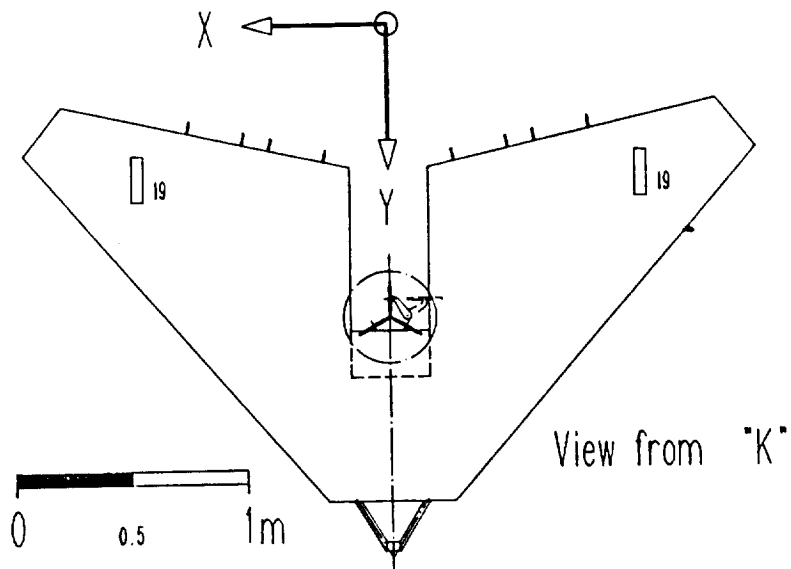
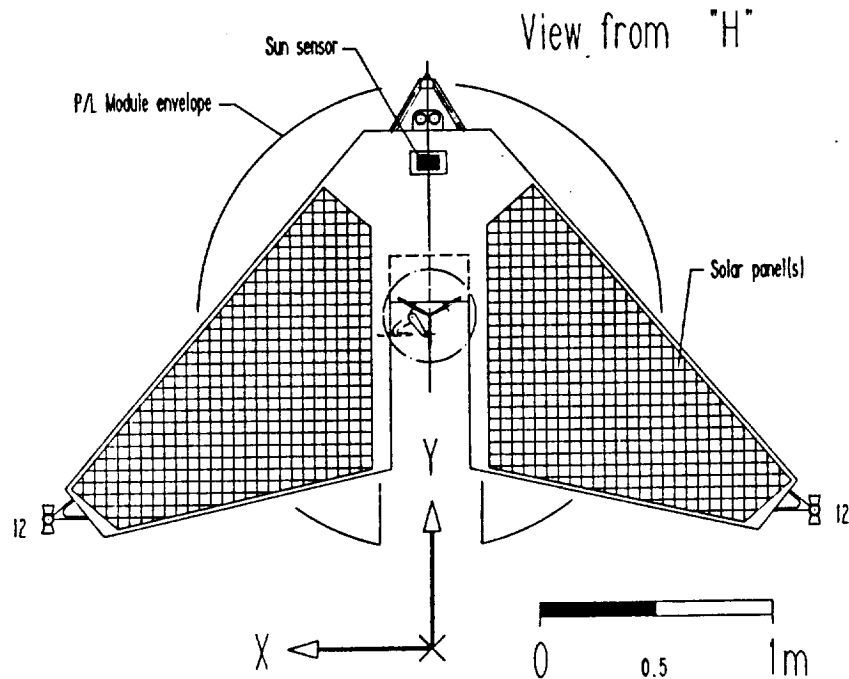
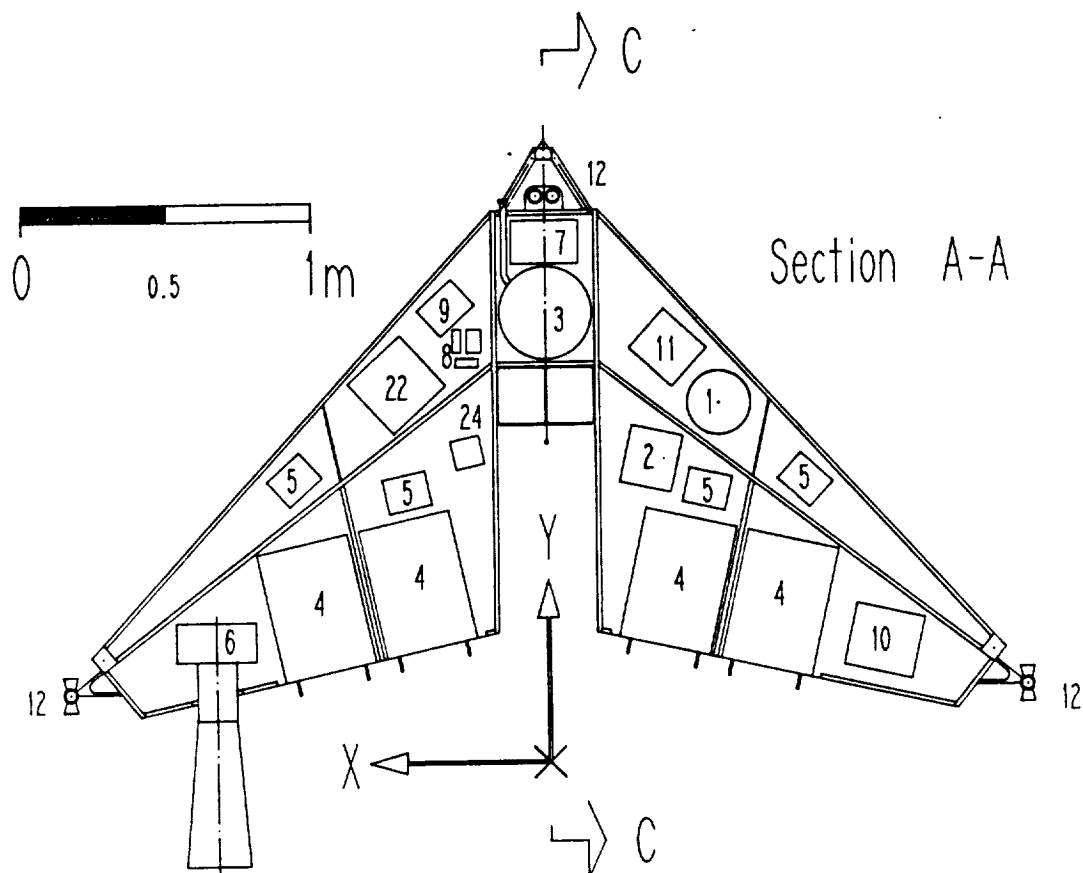


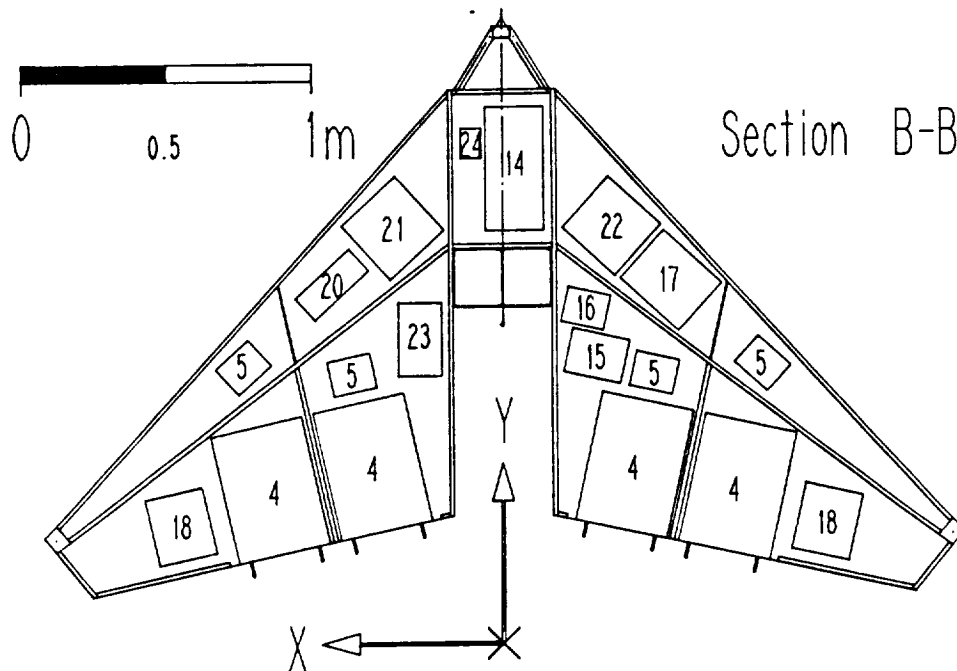
FIG. 4.5-17 SERVICE MODULE - TOP AND BOTTOM VIEWS



- 1 REACTION WHEEL
- 2 WHEEL DRIVE ELECTRONICS
- 3 NITROGEN TANK
- 4 PRIMARY BATTERY
- 5 BATTERY CONTROL UNIT
- 6 STAR TRACKER

- 7 SUN SENSOR ELECTRONICS
- 8 GYROSCOPES
- 9 GYROSCOPES ELECTRONICS
- 10 ADCS COMPUTER
- 11 THRUSTER DRIVE ELECTRONICS
- 12 COLD GAS THRUSTERS

FIG. 4.5-18 LAYOUT OF THE UPPER MODULE



13 ACCELEROMETER
14 PCDU
15 SECONDARY BATTERY
16 BATTERY REGULATION UNIT
17 RFDU
18 S-BAND TRANSPONDER

19 MICROSTRIP ANTENNA
20 DECODER
21 CENTRAL TERMINAL UNIT
22 REMOTE TERMINAL UNIT
23 MASS MEMORY UNIT
24 DRIVE MECH. ELECTRONICS

FIG. 4.5-19 LAYOUT OF THE LOWER MODULE

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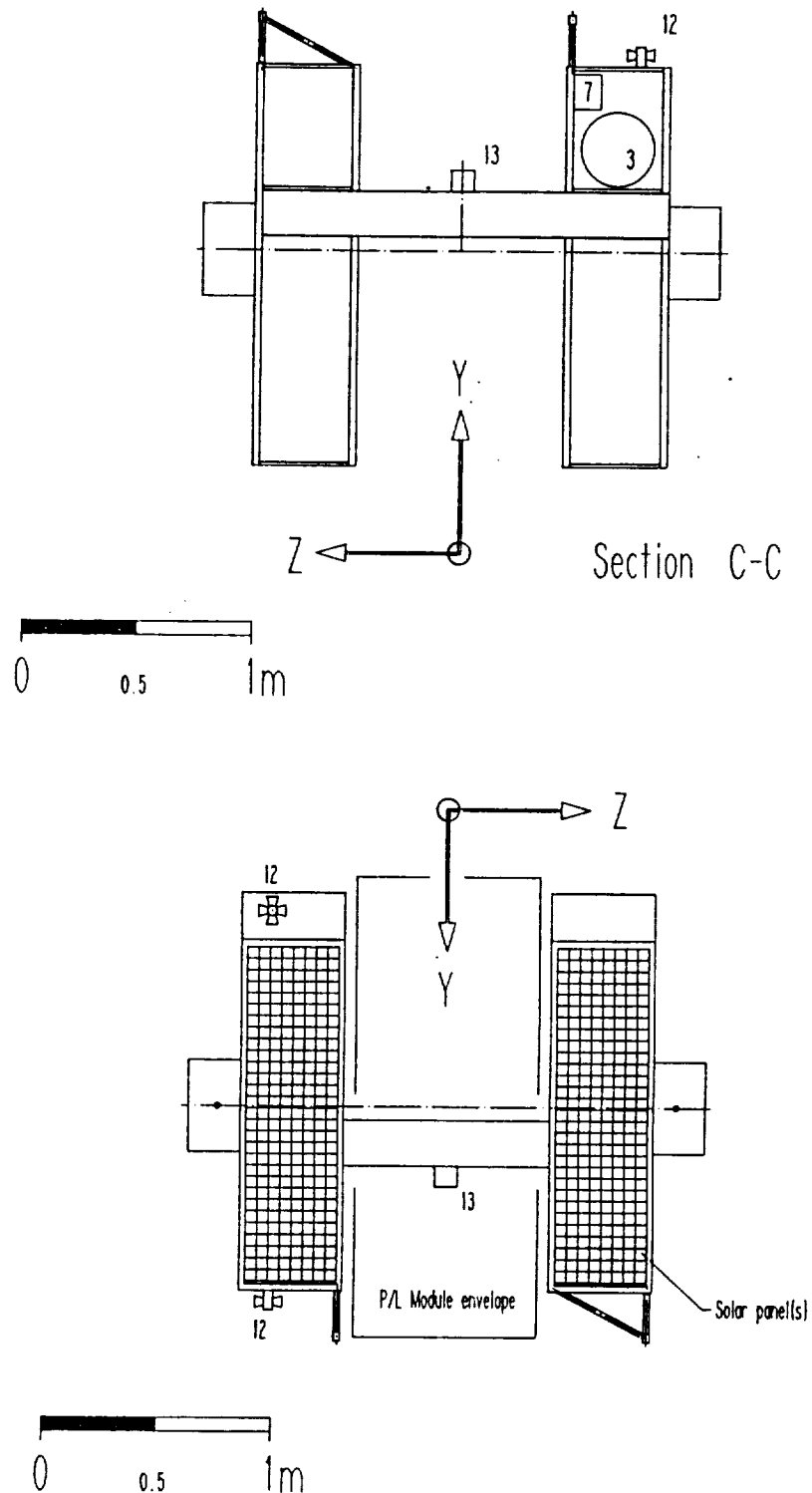


FIG. 4.5-20 SERVICE MODULE - SIDE VIEW

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4.5.2.3 Launcher Mechanical Interfaces

The geometrical compatibility of the reeling system and of the Elevator with the STS cargo-bay has been verified.

Figure 4.5-21 shows a possible mounting of the reeling system inside the STS cargo-bay (dynamic envelope); the attachment scheme could be a "3- point" isostatic fitting, where the carrier longerons react longitudinal and vertical loads (F_x & F_z STS ref. frame) and the keel fitting reacts side and longitudinal loads. The Figure shows furthermore the possibility to slightly increase the overall reeling system dimensions.

Figure 4.5-22 demonstrates a possible Elevator mounting inside the STS cargo-bay without pallet use; in this case the extension of the Elevator "V" beams toward the Space Shuttle longerons allows an easy way to interface. The keel fitting is also present.

Figures 4.5-23 and 4.5-24 show a feasible mounting of the Elevator inside the STS cargo-bay using a "pallet". Although the mechanical interfaces should be designed according to the pallet requirements, we can envisage two keel fittings (one for each "V" beam bottom as in Figure 4.5-24 numbers 12 and 13) reacting longitudinal (X), transversal (Y,Z) loads and torque around Y and Z axes.

Torques around X axis are counteracted by means of rods connecting the "V" beam tips with the sill pallet hardpoints.

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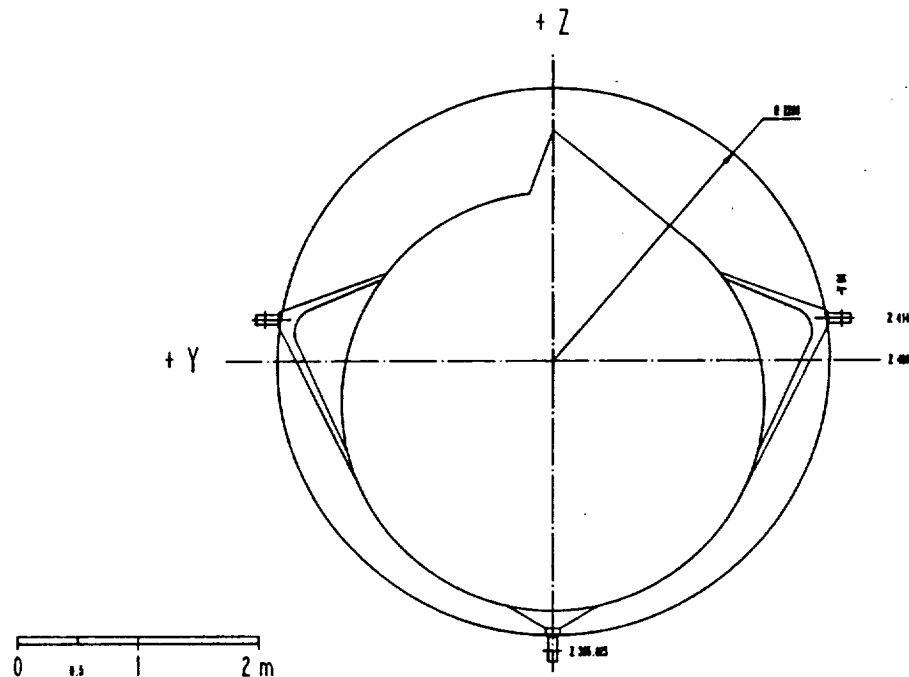


FIG. 4.5-21 REELING SYSTEM INSIDE STS CARGO-BAY

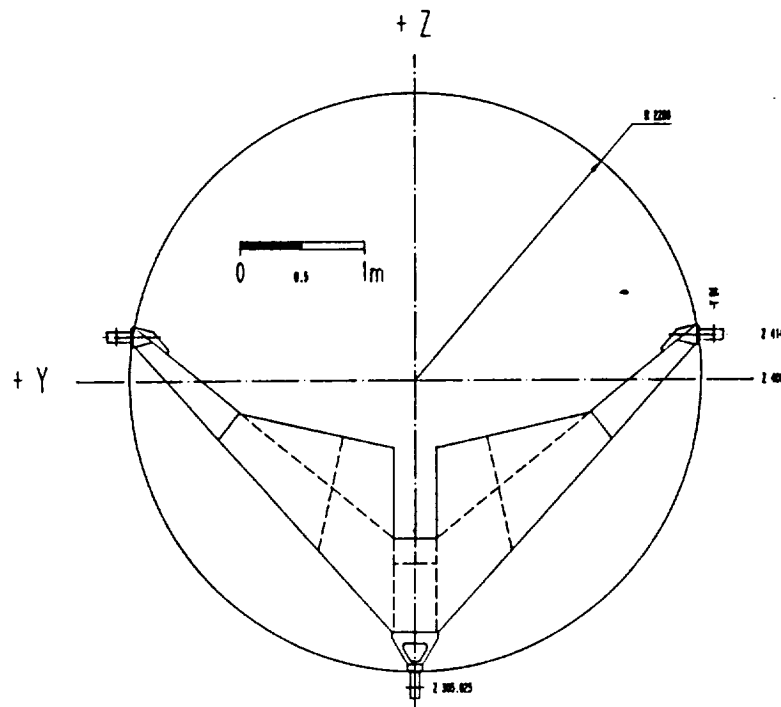


FIG. 4.5-22 ELEVATOR INSIDE STS CARGO-BAY (NO PALLET)

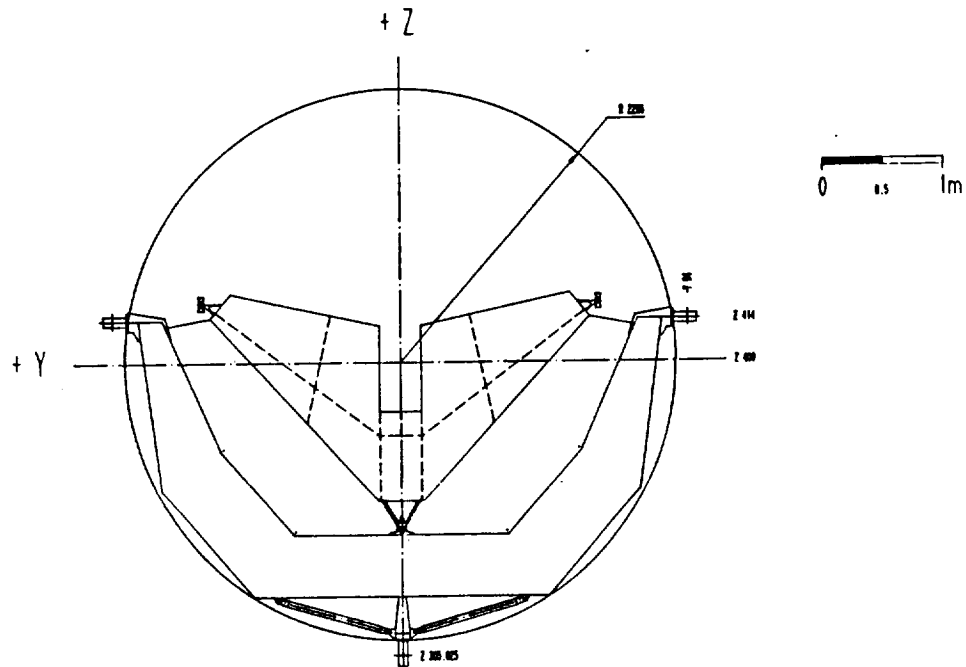


FIG. 4.5-23 ELEVATOR ON PALLET INSIDE STS CARGO-BAY

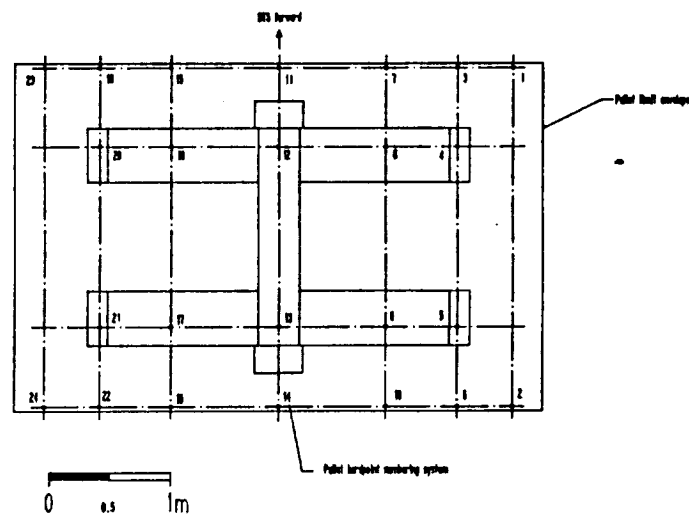


FIG. 4.5-24 ELEVATOR ON PALLET (INTERFACES)

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4.5.2.4 Subsystems Preliminary Design

4.5.2.4.1 Elevator Structure

The Elevator structure is mainly composed of two identical modules (containing the equipment) connected by a central beam as illustrated in Figure 4.5-25.

At the ends of the central beam there are two "V" shaped beams, similar to boomerangs, on which profiled sandwich plates are connected.

In this way part of the load (e.g. batteries) is transmitted to the "V" beams by means of transversal panels acting as ribs while the remaining load (see equipment layout) acts directly on the beams.

Clearly the "V" beams should be capable (once the integration is done) to counteract torsional loads and hence they should be closed sections; removable panels for equipment integration are foreseen.

At the "V" beam tips there is a set of diffusion points to interface the pallet sill hardpoints while at their bottom, struts interface the pallet keel hardpoints.

The central beam could be a typical 2-cells closed section manufactured in C.F.R.P. .

The material of the other structural elements could be Aluminum alloy sandwich type.

Figure 4.5-26 shows the changing of the proposed structural configuration in case of pallet rejection.

It is clear that the extension of the Elevator "V" beams does not produce a sensible structural complication.

The only warning to notify is the essential displacement of the Elevator center of mass from the theoretical tightening point; a non-negligible ballast mass increase is hence foreseen.

The resulting mass of the overall Elevator structure is 81.2 Kg, including a 20% contingency factor.

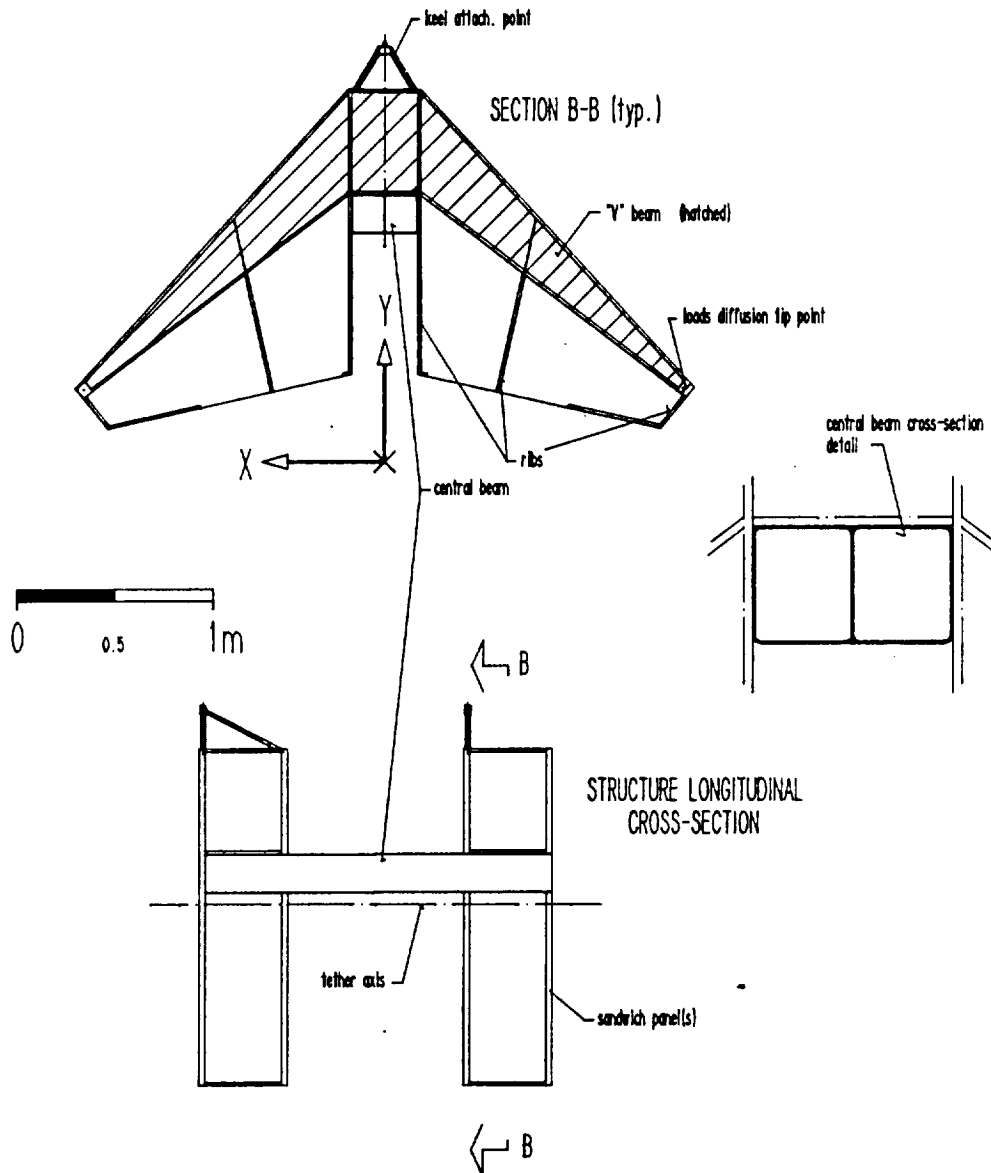


FIG. 4.5-25

ELEVATOR STRUCTURE

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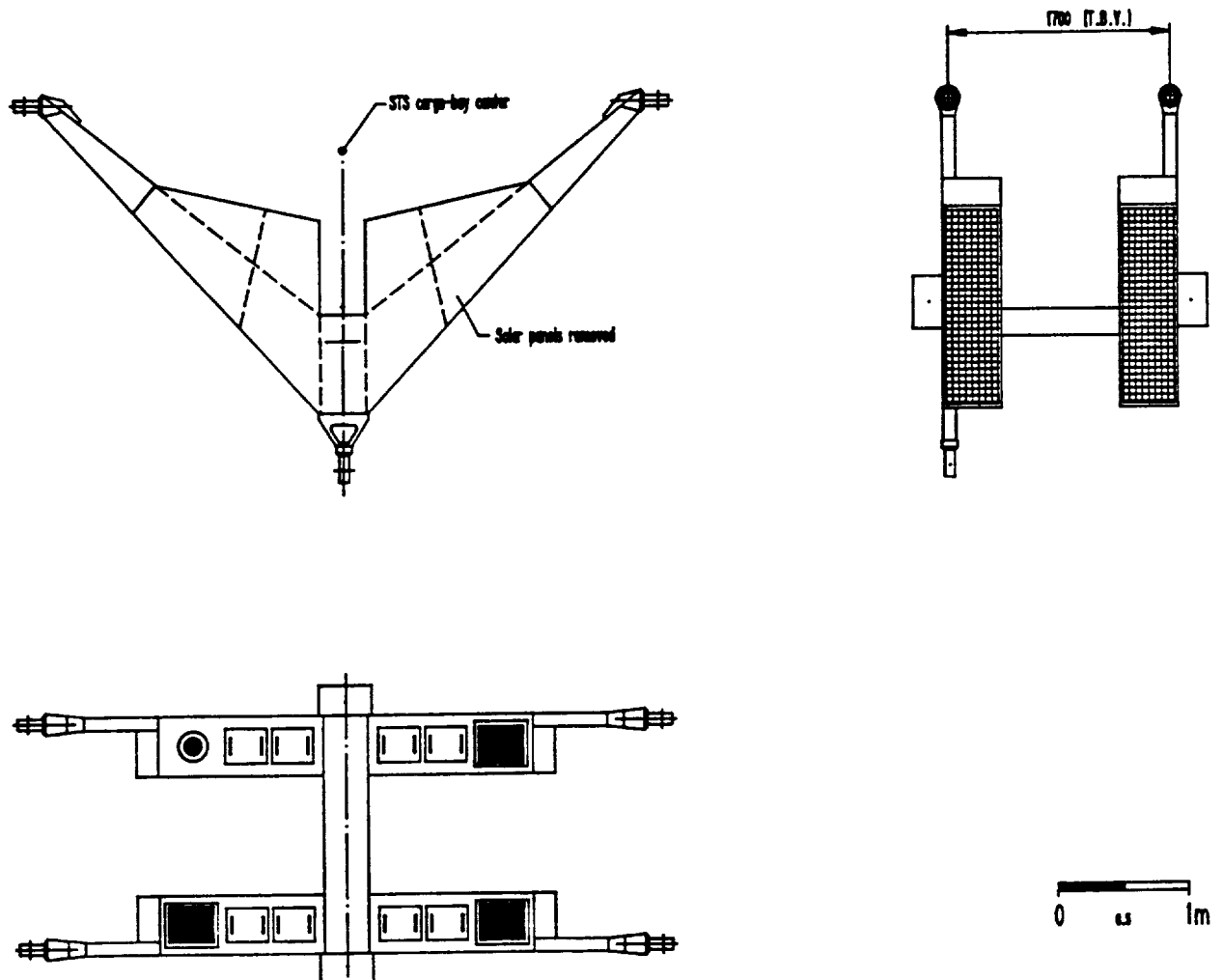


FIG. 4.5-26 ELEVATOR STRUCTURAL CONFIGURATION (NO PALLET)

4.5.2.4.2 Power Subsystem

The Power Subsystem (EPDS) must be able to provide the specified electrical power for all the spacecraft subsystems during:

- a) the nominal mission (including the transfer and the station keeping phases), whose duration is foreseen between one week and one month,
- b) all the time in which, after nominal mission, the Elevator is required to stay on the tether due to the impossibility of immediate recovery (in this case the Elevator enters a "survival mode" in which only the telecommunication and some of the thermal and attitude control functions are ensured).

In the first case the EPDS must ensure an average power of about 200 W to the various subsystems (see Section 4.4.2.2), and fulfil the power requirement of the Payload Module.

In the second situation the load is reduced to about 140 W but the period of time during which this power must be supplied cannot be determined in advance and could be also very long.

Power during the nominal mission is provided by a set of primary Li/SOCl₂ batteries, and by about 5.6 m² of body-mounted solar arrays which, in the nominal flight attitude of the VGL, are equivalent to a normally illuminated solar panel with area ranging from 2 to 3 m².

The Service Module is designed for accommodating up to eight 45x32x26-cm batteries. The number of batteries and the number of cells in each battery to be used in the various missions is function of the payload power demand.

The mean power available for different mission durations, under the hypothesis of using all the eight batteries, is shown in Fig.4.5-27.

In the survival mode, the required power is provided by the solar panels (in sunlight) and by one 5-kg NiH₂ rechargeable battery (in eclipse).

The concept of the EPDS design is that it is virtually autonomous with Space Station (or ground) intervention only necessary for the reconfiguration of the power generation system, or in the event of failures.

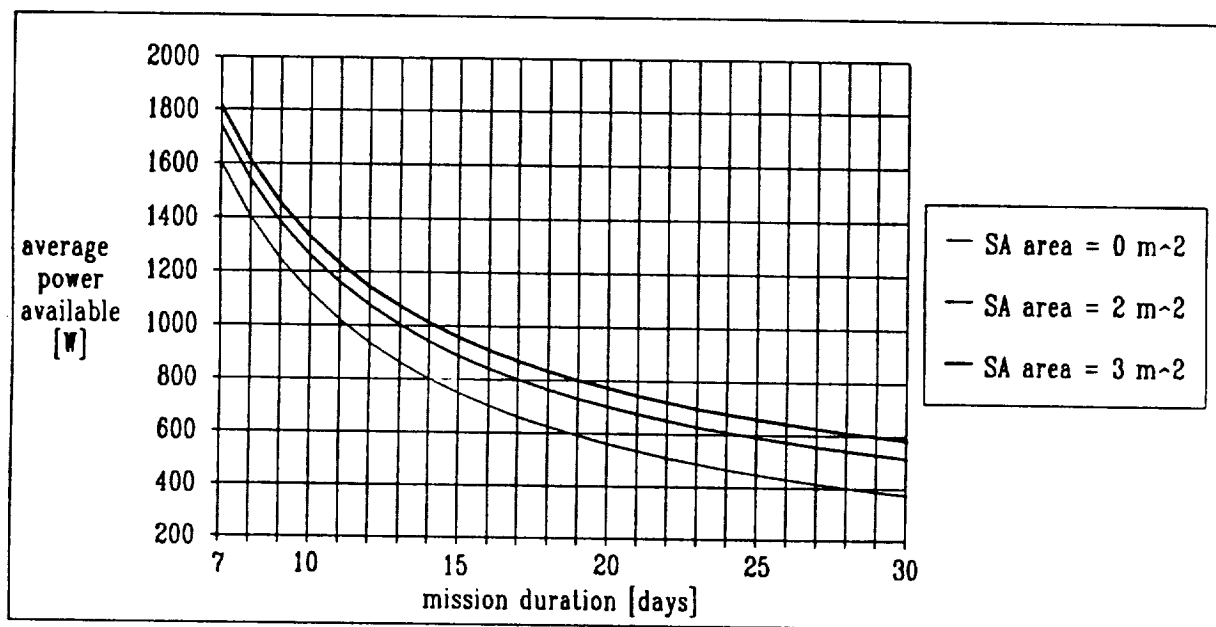


FIG. 4.5-27 AVAILABLE AVERAGE POWER VS MISSION DURATION WITH 624 Kg OF Li/SOCl_2 BATTERIES AND DIFFERENT SOLAR ARRAYS EFFECTIVE AREAS

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A Battery Regulation Unit (BRU) controls the charge and discharge operations of the NiH_2 battery, and provides continuous monitoring of the battery voltage, current, temperature.

The same monitoring functions for the primary batteries are ensured by the Battery Control Unit (BCU). The overall power distribution, the solar arrays regulation, as well as the control of the Main Bus are managed by a Power Control and Distribution Unit (PCDU).

Preliminary estimate of the mass and the power consumption of the EPDS components is in the following Table.

UNIT	NUMBER OF UNITS	UNIT MASS [Kg]	TOTAL MASS [Kg]	UNIT POWER [W]	TOTAL POWER [W]
PRIMARY BATTERY	8	78.0	624.0	-----	-----
SECONDARY BATTERY	1	5.0	5.0	-----	-----
SOLAR PANELS	5.6 m ²	3.3Kg/m ²	18.5	-----	-----
BCU	8	1.5	12.0	2.0	16.0
BRU	1	2.5	2.5	6.0	6.0
PCDU	1	17.0	17.0	10.0	10.0
TOTAL	-----	-----	679.0	-----	32.0

TABLE 4.4 PRELIMINARY EPDS HARDWARE ESTIMATE

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4.5.2.4.3 Attitude Determination and Control Subsystem

The Attitude Determination and Control Subsystem (ADCS) must perform the following operations:

- o acquisition of all the information necessary for the reconstruction of the motion of the Elevator about its CM.
- o perform the attitude maneuvers required to bring the Elevator in the attitude established for the mission after the release from the Space Station, and to bring it back in the docking position at the end of the operative phase.
- o maintain the Elevator in the nominal attitude during the mission.

The first task is accomplished by using a set of sensors including three rate gyros providing the angular rates about the Elevator principal axes, a star tracker and a digital sun sensor, for measuring the pitch, roll, yaw angles and for updating the gyros attitude reference.

When the Elevator is in the nominal flight attitude, the star tracker looks in the out of plane direction and provides a direct measure of the roll and yaw angles (θ_x and θ_z respectively) all along the orbit with an accuracy of 10 arcsec.

The sun sensor, which axis is aligned along the -Z axis, measures the angle ϕ between -Z and the sun direction when the sun is in the sensor FOV (about $90^\circ \times 90^\circ$) with an accuracy of 0.01° . This measure, together with the knowledge of the sun coordinates, the true anomaly of the Elevator, and the roll angle, allows in turn to compute the value of the pitch angle (θ_y). During the orbit arc in which the sun is out of the sensor FOV, the value of θ_y is determined by integrating the angular velocity $d\theta_y/dt$ obtained from the gyro-package.

Gyros are used alone in the rotation maneuver around the tether axis required to pass from the docking attitude to the operative one and viceversa, and in all the other possible attitude maneuvers of the Elevator. As it has been shown in the Section 4.4.3, the tension of tether itself is sufficient to counteract the Elevator rotations about the pitch and roll axes.

Therefore the maintenance of the system in the nominal flight attitude requires in principle only the control of the rotations around the Z-axis (yaw-axis). To this end a magnetic bearing reaction wheel seems the most appropriate device as it allows very smooth attitude corrections, essential requirement for a system carrying microgravity experiments.

The same wheel allows also to perform the rotation of the Elevator around the tether axis in a very smooth manner, so minimizing the oscillation induced in the tether itself by this maneuver.

From a preliminary evaluation of the disturbing torques about the yaw axis and of the moments of inertia of the Elevator it seems that even a small reaction wheel (momentum storage capacity = ± 2 Nms, max. reaction torque = 0.1 Nm) could be sufficient both for controlling and changing the Elevator attitude.

In presence of a secular torque of the order of 10^{-4} Nm, like the one generated by the air drag, such a wheel requires to be off-loaded about every 11 hours. A rotation of the Elevator through an angle of 90° about the tether axis is instead achieved in about 10 minutes.

Three passive oscillation dampers, acting around the principal axes, and twelve 20 mN cold gas thrusters complete the set of the attitude control actuators.

The 12 thrusters are located in such a way to make possible the provision of pure torques on the three axes, i.e. without generating any force on the CM (see Fig.4.5-28). The available torques about X, Y, Z-axis are listed in Table-4.5 as a function of the thruster force F. The main functions of the thrusters are the off-loading the reaction wheel (yaw thrusters), the damping of large oscillations of the Elevator, and the execution of the attitude maneuver required by every possible emergency situation.

The commands for the actuators are generated by a dedicated ADCS Computer according to the selected control law based on the angles and angular rates provided by the measurement assembly.

The Wheel Drive Electronics (WDE) determines the torque, speed, and speed direction of the wheel on the basis of the command received from the computer.

Analogously, the Thruster Drive Electronics (TDE) constitutes the interface between the 12 thrusters and the ADCS Computer.

Preliminary estimate of the mass and the power consumption of the ADCS components is in Table-4.6.

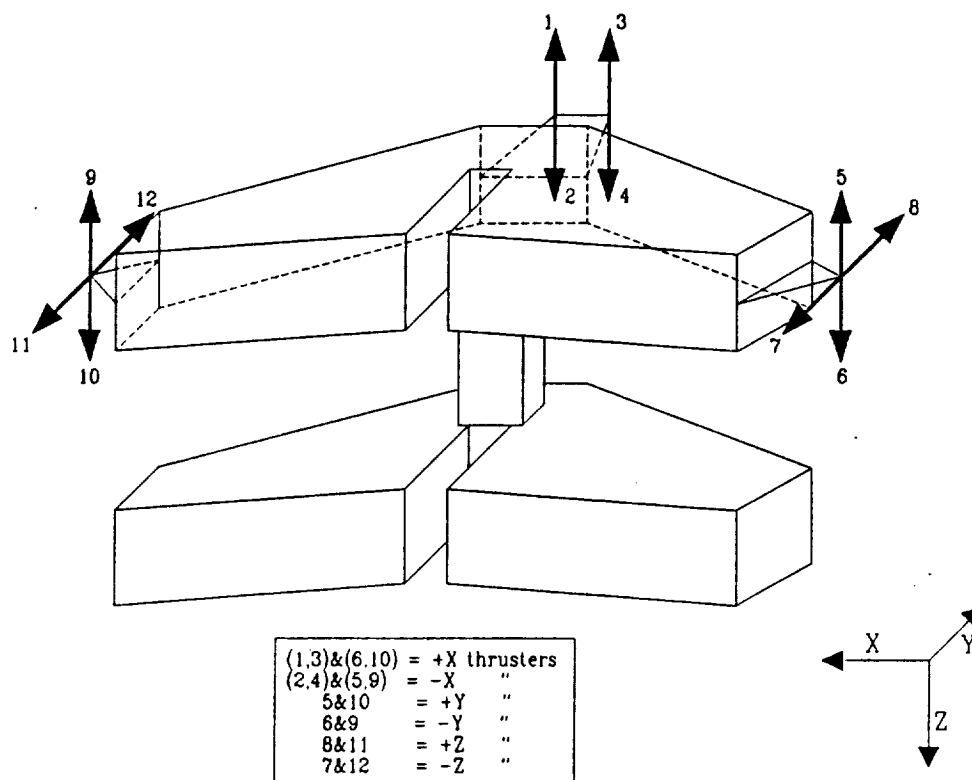


FIG. 4.5-28 THRUSTERS IMPLEMENTATION

THRUSTERS	TORQUES [Nm]		
N°	Tx	Ty	Tz
(1,3)&(6,10)	+3.4F	0	0
(2,4)&(5,9)	-3.4F	0	0
5&10	0	+3.3F	0
6&9	0	-3.3F	0
8&11	0	0	+3.3F
7&12	0	0	-3.3F

TABLE 4.5 THRUSTERS TORQUE CONTRIBUTIONS (F = 0.02 N)

UNIT	NUMBER OF UNITS	UNIT MASS [Kg]	TOTAL MASS [Kg]	UNIT POWER [W]	TOTAL POWER [W]
STAR TRACKER (optical head + electronics)	1	7.5	7.5	16.0	16.0
SUN SENSOR (optical head + electronics)	1	3.4	3.4	1.0	1.0
RATE GYRO	3	1.1	3.3	3.5	10.5
GYRO ELECTRONICS	1	7.1	7.1	19.5	19.5
REACTION WHEEL	1	3.0	3.0	(2) 3.0	3.0
WHEEL DRIVE ELECTRONICS	1	2.0	2.0	(2) 5.0	5.0
DAMPER	3	2.0	6.0	-----	-----
(1) NITROGEN TANK	1	7.2	7.2	-----	-----
THRUSTER	12	0.1	1.2	(firing) 6.0	(3) 24.0
THRUSTER DRIVE ELECTRONICS	1	3.0	3.0	2.0	2.0
TUBING	1 SET	2	2	-----	-----
ADCS COMPUTER	1	8.6	8.6	10.0	10.0
TOTAL	-----	-----	54.3	-----	82.0

TABLE 4.6 PRELIMINARY ADCS HARDWARE ESTIMATE

- Notes: (1) Dry mass. The selected tank can store up to 4 Kg of N₂ at 250 atmosphere pressure.
(2) Steady state consumption.
Max wheel consumption (at max torque and max speed) = 30 W.
Max WDE consumption (at max torque and max speed of the wheel) = 10 W.
(3) 4 thrusters on. It is not foreseen to fire more than 4 thrusters simultaneously.

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4.5.2.4.4 Thermal Control

The major problem to be faced in the design of the Thermal Control Subsystem (TCS) of the Elevator concerns the extremely different thermal requirements, coming from all the possible microgravity payloads, that must be fulfilled by this subsystem.

Among the various possible options, an active thermal control, based on pumped fluid loop, is the only solution which has the flexibility level required to deal with a wide range of heat loads with a minimum of hardware modification, maximum confidence level, and minimum testing.

Nevertheless, the pump package required by such a system produces disturbing accelerations which may turn out to be unacceptable for the microgravity experiment in progress.

In addition the interfacing of the fluid loop between the Service and the Payload Module is a very critical task (this point is a serious drawback even for a heat pipes based system).

To overcome these problems it has been decided to adopt a different design philosophy consisting in uncoupling thermally the Payload Module from the Service Module and providing them with two autonomous thermal control systems. The TCS of the Payload Module, is tailored, mission by mission, to the particular needs of the installed experiments.

A TCS suitable for the Service Module could be constituted by a semi-active system, based on the use of variable conductance heat pipes (VCHP). A purely passive system, instead, doesn't seem able to match with the large variations foreseen on radiative environment.

Service Module internal dissipation is rejected to space by three radiators (two on the lower module and one on the upper module) placed on the -Y side; when the Elevator is in the nominal flight attitude, no direct sunshine is received by this surface. The rejection capability includes:

- all heat generated by equipment using electrical power and, in particular, by the batteries;
- all excessive heat absorbed from the environment (note that the sides covered by solar cells cannot be thermally insulated to avoid an overheating of the cells itself).

A system of VCHP is the means by which the internal heat is collected and transferred to the radiators. Moreover, their variable conductance capability is exploited to reduce heat rejection during eclipses thus preventing the need of excessive heaters power in these cold mission phases.

All the sidewalls of the Service Module (except the radiators and solar panels) are covered with MLI blankets to minimize suffering from the variable input radiation of the external environment.

A very preliminary estimate of mass and power allocated to the TCS units mounted on the Service Module is given in the following Table. The 10% contingency margin takes into account the present uncertainties about VCHP's and thermostatically controlled heaters arrangement.

UNIT	NUMBER OF UNITS	UNIT MASS [Kg]	TOTAL MASS [Kg]	UNIT POWER [W]	TOTAL POWER [W]
RADIATOR	3	2.0	6.0	-----	-----
VCHP			30.0		15
HEATERS			3.0		50 (*)
THERMOSTATS + THERMISTORS			2.5	-----	-----
MLI BLANKETS	13 m ²	0.8 [Kg/m ²]	10.4	-----	-----
TOTAL	-----	-----	51.9	-----	65
+ 10% MARGIN			57.1	-----	71.5

TABLE 4.7 TENTATIVE TCS POWER AND MASS BUDGET

(*) Max. estimate heaters consumption during eclipses.

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4.5.2.4.5 Elevator Positioning Subsystem

The "Elevator Positioning Subsystem" doesn't belong to the standard subsystems set of a spacecraft.

Its function is peculiar to the VGL and consists in:

- 1) the determination of the position of Elevator with reference of the CG of the overall system (Space Station + Elevator + tether + ballast);
- 2) the determination of the position and velocity of the Elevator with reference to the Space Station, and its travelled tether length;
- 3) the movement of the Elevator along the tether, and its positioning at the desired gravity level.

The first function is fundamental for the knowledge of the (quasi-)steady components of the acceleration (essentially due to the gravity gradient) occurring inside the Elevator, which, in turn, is required for the positioning of the laboratory at the chosen gravity level among the available ones.

This task could be accomplished by means of a laser ranging system (ISS based), supported by a set of accelerometers, capable to detect and provide in real time very low frequency accelerations, and placed as near as possible to the Elevator CG.

The same accelerometers could also carry out the monitoring function of the microgravity environment in the lowest region of the frequency spectrum in the way required by the experiments (the accelerometers sensitive to the higher frequency signals, instead, are mounted directly on the Payload Module, as near as possible to the experiments).

The information on the position/velocity of the Elevator on the tether relative to the ISS are particularly important for the deployment/retrieval operations, and, together with the accelerometer data, for commanding the Elevator motion along the tether itself.

The position/velocity of the Elevator with reference to the ISS could be accurately determined by using, for instance, a ISS based ranging and tracking laser system including range rate measure. On the contrary, the travelled tether length and, if necessary, the travelling speed, can more easily be measured on board the Elevator itself. Notice that the travelled tether length is different from the position w.r.to the Space Station if the tether is arched.

Different possibilities for the motion drive mechanism have been examined (Ref. paragraph 4.4.1). The selected solution consists of two sets of three wheels placed externally on the $\pm Z$ sides of the Elevator:

- one of the two wheel sets is provided by two electric motors (in redundancy) and is the actuator of the Elevator motion.
- the other set acts as a guide for the tether and includes a braking system to be used during station keeping phases.

Two drive mechanism electronics (in redundancy) command the wheel motor according to the required control law, and provide the measurement of the travelled tether length through the count of the wheel turns.

A preliminary mass and power consumption evaluation of the components of the Elevator Positioning Subsystem mounted on the Elevator is given in Table-4.8.

UNIT	NUMBER OF UNITS	UNIT MASS [Kg]	TOTAL MASS [Kg]	UNIT POWER [W]	TOTAL POWER [W]
ACCELEROMETER (TRIAxIAL)	1	3.0	3.0	15.0	15.0
DRIVE MECH. 1 (WHEELS+MOTORS)	1	4.0	4.0	(1) 10.0	10.0
DRIVE MECH. 2 (WHEELS+BRAKE)	1	4.0	4.0	-----	-----
DRIVE MECH. ELECTRONICS	2	1.0	2.0	(1) 5.0	(2) 5.0
TOTAL	-----	-----	13.0	-----	30.0

TABLE 4.8 PRELIMINARY "Elevator Positioning Subsystem"
HARDWARE ESTIMATE

(1) Wheels Motor ON

(2) The two electronics are not ON at the same time

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4.5.2.4.6 Telecommunications

During any VGL mission a RF link is established between the Elevator and the Space Station through a telecommunication system operating in the S-band frequency. No direct link between the Elevator and ground stations is foreseen at the moment.

The VGL TT&C subsystem must ensure the following functions:

- o command: uplink from the ISS to the Elevator for transmission of telecommands;
- o telemetry: Elevator-to-ISS housekeeping (including the attitude sensors measurement) and science data link;
- o tracking: relative range and range rate measurement capability.

The envisaged bit rates are respectively:

uplink : 4 kb/s
downlink: 100 kb/s (housekeeping + science data).

For some experiments (especially those requiring video images) this downlink bit rate could be insufficient for transmitting in real time all the data. In this case only the data necessary for monitoring the most critical parameters of the experiment are directly transmitted, while the other ones are stored on-board the Elevator and recovered at the end of the mission.

The TT&C subsystem consists of the following units:

- Two S-band microstrip antennas (in redundancy) placed on the side of the Elevator towards the Space Station
- Two transponders (in redundancy), each composed of S-band receiver and transmitter.
- One S-band RF Distribution Unit (RFDU) interconnecting the transponders to the antennas.

A preliminary mass and power consumption evaluation of the components of the VGL TT&C subsystem is given in Table-4.9.

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UNIT	NUMBER OF UNITS	UNIT MASS [Kg]	TOTAL MASS [Kg]	UNIT POWER [W]	TOTAL POWER [W]
RFDU	1	1.5	1.5	-----	-----
TRANSPONDER	2	4.0	8.0	26	26 *
MICROSTRIP ANTENNA	2	0.2	0.4	-----	-----
COAXIAL CABLES	2	0.2	0.4	-----	-----
TOTAL	-----	-----	10.3	-----	26

TABLE 4.9 PRELIMINARY TT&C HARDWARE ESTIMATE

* The two transponder are never ON in the same time.

4.5.2.4.7 On-Board Data Handling

The main functions to be implemented the Data Handling (OBDH) subsystem are:

- o Telecommand reception
- o Telecommand distribution
- o Housekeeping data collection
- o Payload data collection
- o Downlink telemetry data stream generation
- o Mass Memory Unit management
- o On-board time keeping
- o On-board time distribution
- o Time-tag command handling
- o Provide an autotest function to verify the correct working of all the subsystems.

The VGL OBDH consists of the following functional units:

- One Decoder
- One Central Terminal Unit (CTU), with associated Software Memory Unit (SMU)
- A Mass Memory Unit (MMU)
- Two Service Module Remote Terminal Unit (RTU) (one for each equipment platform)
- One Payload RTU

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- Digital Bus Unit (DBU)
- A physical link, the OBDH Data Bus, equipped with Block Transfer Bus.

Each unit is provided with internal redundancy in order to ensure a single point failure tolerance to the overall OBDH subsystem.

The Decoder receives the telecommand video signals from the TT&C transponder and performs the following main tasks:

1. detection of the presence of the carrier signal indicated by lock status information
2. send the video signal to demodulator
3. demodulation of modulated subcarrier signals, testing of the modulated signals for proper and valid content and decoding of the validated data
4. distribution of the decoded data to the CTU for further processing and subsequent distribution over the OBDH bus
5. distribution of the "High Priority Commands" directly to the Elevator subsystems.

The CTU is the node which controls all the OBDH data bus traffic.

It acquires from the Decoder the telecommands uplinked by the Space Station and distributes them in the proper time, and collects the experiments and Elevator subsystems data using the DBU and the RTU's. The collected data to be transmitted in real time are then formatted, encoded, and modulated by the CTU, and the resulting signal is provided to the S-band transmitter. The scientific data which cannot be downlinked directly to the Space Station, as their bit rate exceeds the transmission capability of the TT&C subsystem, are instead sent to MMU for storage.

A precise sizing of the MMU will be made when more information about the data flux generated by each experiment running on the Elevator will be available.

On-board time keeping is another vital CTU function: a master-clock oscillator provides timing, control, and synchronization signals to experiments and subsystems. All the CTU operations are under the control of one microprocessor; the basic software for performing the OBDH functions is stored in the SMU. There is a minimum of payload processing applications in the OBDH subsystems, as the experiments will be "intelligent users" and therefore able to perform their own on-board data processing as required.

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The RTU's are the input/output terminals of the OBDH subsystem. Their functions include the acquisition of different kinds of data, the distribution of commands, and the distribution of special signals.

The DBU represent the physical layer of the interface in the OBDH. This unit operates like a modem. The Data Bus is a full-duplex system composed by:

1. Interrogation Bus
2. Response Bus
3. Block Transfer Bus.

The unit is fully redundant to grant user to have an interface for each process; a cross-coupling is foreseen toward the redundant OBDH bus.

Preliminary estimate of the mass and the power consumption of the OBDH units is in Table-4.10. The 10% contingency margin takes into account the current uncertainties about the MMU characteristics.

UNIT	NUMBER OF UNITS	UNIT MASS [Kg]	TOTAL MASS [Kg]	UNIT POWER [W]	TOTAL POWER [W]
DECODER	1	3.5	3.5	6	6
CTU	1	5.0	5.0	13	13
MMU	1	14.0	14.0	7	7
RTU	3	4.5	13.5	3	9
DBU	1	1.0	1.0	----	----
TOTAL	-----	-----	37.0	-----	35
+ 10% MARGIN			40.7	-----	38.5

TABLE 4.10 PRELIMINARY OBDH HARDWARE ESTIMATE

4.5.2.5 Mass and Power Budgets

A mass and power consumption breakdown of each subsystem of the Service Module. (SM) is found in the appropriate chapter.

The global mass budget of the Elevator is as follows:

Subsystem	Mass [Kg]
Structure	81.2
Power Subsystem	679.0
ADCS	54.3
Thermal Control	57.1
Positioning Subsystem	13.0
Telecommunications	10.3
OBDH	40.7
Harness (rough estimate)	30.0
Balance Mass (rough est.)	30.0
TOTAL SM DRY MASS	995.6
PROPELLANT (N₂)	4.0
PAYLOAD MODULE MASS	1000.0 (*)
MAX ELEVATOR MASS	1999.6

TABLE 4.11 ELEVATOR MASS BUDGET

(*) Maximum value for the mass of the Payload Module

The following Table gives the power budget in the various mission phases. The following cases are distinguished:

- operational mode: Elevator stationary at a fixed altitude, experiments in progress.
- transfer mode: Elevator moved along the tether, experiments switched off.
- survival mode: Elevator stationary at a fixed altitude, experiments switched off.

Subsystem	Power [W]		
	Operational Mode	Transfer Mode	Survival Mode
	av. -- max	av. -- max	
Power Subsystem	26	26	16
ADCS	58 - 114	58 - 114	45
Thermal Control	35 - 71.5	35 - 71.5	35
Positioning Subsystem	15	30	2
Telecommunications	26	26	26
OBDH	38.5	27.5	16
TOTAL SM POWER	198.5 - 291	202.5 - 295	140

TABLE 4.12 POWER BUDGET

It can be noted that mass and power consumption estimated for each subsystems are based on the characteristics of state-of-the-art hardware. Therefore, in view of a probable improvement of the performances of the components for space application, the above budgets must be considered conservative.

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4.5.3 PAYLOAD ACCOMMODATION

In order to provide the VGL with a high degree of flexibility in accommodating payloads with very different characteristics, the scientific experiments are hosted in a module separable from the Elevator, reconfigurable mission by mission in function of the requirements (volume, heat rejection, etc..) of the experiments themselves.

Moreover, the possibility of separating the Payload Module, allows the substitution of the experimental apparatus without the necessity of detaching the whole Elevator from its ISS interface, and its moving to the assembly facility (which could be also ground based).

The design of the Payload Module(s) requires a detailed knowledge of the experimental facilities to be used and it is beyond the aim of this study. Purpose of this chapter is to provide a set of preliminary design drivers for the Payload Module configuration based on the results of the overall Elevator basic design activity, and of a preliminary investigation about the resource requirements of the possible VGL payloads.

4.5.3.1 Proposed Experiment Flashback and Basic Assumptions

"Low Gravity Processes Identification Report" [15] gives a detailed description of the experimental needs pointed out during the course of the study, together with the residual acceleration requirements felt necessary to meet the experimental aims.

A brief summary of the proposed experimental areas to be covered on board the VGL is reported here (see Table-4.13) to allow an easier understanding of the physical/functional requirements posed by the scientific payload on the Payload Module design.

Starting from these experiments, a preliminary investigation was performed aiming at obtaining a corresponding list of facilities capable to carry out the mentioned experimental topics.

Obviously, pretending to have a well defined and exhaustive scenario of the possible payloads to be boarded on the Elevator is a too ambitious purpose, now, both for reasons of preliminary definition of the experimental aims, and, even more, because the choice of concrete

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facilities (adapted or ad hoc conceived) will be performed in future out of a presently unknown ensemble. However, the goal being the preliminary evaluation of the envelope of the most demanding requirements raised by the facilities, it is estimated that "approximating" the future facilities with the presently available ones (trying, eventually, to take into account the consequences of conceptual modifications necessary to upgrade them to variable gravity purposes) is a sufficiently valid criterion.

The single boarded facility option was chosen as a baseline mission philosophy, so that the whole budget of resources can be devoted to the only experiment active during each "variable gravity stop". This permits also to take into account the scientist's recommendation to avoid spurious perturbations to the chosen values of the physical variables at each g-level of interest, since in this way no crossed acceleration interferences among the facilities can be exchanged. Of course, in case that laboratory standard mass, volume and energy budgets are sufficient to host more than one experimental campaign for facilities with low energy / short experiment time requirements, the payload may be allowed to be composed by more than one facility, provided that only one per time is operated.

In general, it is supposed that the facilities will be upgraded to full automation level, including robotics aid when necessary (sample exchange and preservation, spoiled experimental media and/or wastes disposal), since no manned intervention is possible exception made for the planned servicing sessions close to the Space Station.

As a general guideline, experiment diagnostics has to be provided without sparing, aiming at the best exploitation of the experimental opportunity, namely: the collection of the widest and most accurate harvest of data that is possible.

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FLUID STATICS AND DYNAMICS

- . Marangoni convective regimes and transitions
- . Perturbations of flow, thermal, solutal fields inside liquid volumes with/without enclosed bodies

THERMODYNAMICS

- . Ultrasonic wave adsorption
- . Critical phenomena, in general
- . Heat transfer and boiling

PHYSICAL CHEMISTRY

- . Experiments to be defined

COMBUSTION

- . Combustion models testing

CRYSTAL GROWTH FROM VAPOR

- . Best growth conditions search

CRYSTAL GROWTH FROM SOLUTION

- . Best growth conditions definition
- . Supersaturation jumps effects

CRYSTAL GROWTH FROM MELT

- . Growth process models validation
- . Longitudinal and lateral segregation phenomena

METALLURGY

- . Morphological stability of the solidification front
- . Interface tension dependent solidification phenomena
- . Extension of experimentation to convecto-diffusive region
- . Composites production effects investigation

PLANT PHYSIOLOGY

- . Extension of gravitropistic responses investigation range

EXO BIOLOGY

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4.5.3.2 Possible Facilities for the Selected Experiments

A tentative assignment of experimental goals to the presently available facilities is given in Table-4.14. This list was obtained by using basically the document [6] as data source. This document examines the whole of the European facilities presently available. Primarily, automatic facilities conceived for unmanned environment (TEXUS or MASER sounding rockets, EURECA) were chosen. In order to derive a requirement envelope in the sense previously clarified, their single requirements are briefly examined.

The considered requirements are:

- mass
- volume / dimensions
- data rate (input / output)
- electric power
- rejected heat load

It has to be stressed the fact that the facilities included in the mentioned Table are not (necessarily) the ones that will be boarded on the future Variable Gravity Laboratory.

The presently considered ones should undergo conceptual modifications, consisting in separation of parts to be allocated to "common equipment", evolution of diagnostics, sensors, components in general (electronics, etc..).

Resources savings could be obtained following technical evolution.

In the opposite direction, it is well possible that experiments can be performed only by newly conceived facilities, due to the necessity either to modify the dimensions of the experimental region or to change physical parameters or properties, etc., this leading in turn also to possible increase of performances/ resource demands.

In particular, nowadays facilities usually do not have the capability to repeat experiments (serial processing) over a set of samples, a feature that is essential on the contrary to variable gravity purposes.

Visualization and recording means (photo-, video- and cine-cameras) are necessary for all those areas where transparent substances are present (practically only

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metallurgy and crystal growth from melt are excluded),
and the related facilities could be endowed with in-
creased capabilities.

A definition of sets of science requirements per each
experimental goal is - in other words - necessary to
depict a valid "assignment" to present facilities or to
define the profiles of new ones.

In this light, it is not possible to derive "true"
figures for the mentioned requirements in a
deterministic way.

However, it is possible to deal in a statistical way
with mean values of presently existing experimental
hardware in order to check whether the Payload Module
grants an amount of resources compatible with the
expectable requests of the experimental facilities.

EXPERIMENTAL AREA	FACILITY	CARRIER
FLUID STATICS AND DYNAMICS	Fluid Science Module	MASER
	Bubble Drop and Particle Unit, Fluid Physics Module, HOLOP	SPACELAB
	TEM-06	TEXUS
THERMODYNAMICS and PHYSICAL CHEMISTRY	High Precision Thermostat, HOLOP	SPACELAB
	TEM-06	TEXUS
COMBUSTION	no existing facilities for on-orbit experiments up to now	
CRYSTAL GROWTH FROM VAPOR	Vapor Crystal Growth Facility	SPACELAB
	Automatic Mirror Furnace, MFA	EURECA
CRYSTAL GROWTH FROM SOLUTION	Solution Growth Facility Automatic Mirror Furnace, MFA	EURECA
CRYSTAL GROWTH FROM MELT	Multi-Furnace Assembly	EURECA
	TEM-01, TEM-02	TEXUS
METALLURGY (including Composites)	Multi-Furnace Assembly	EURECA
	TEM-01, TEM-03	TEXUS
PLANT PHYSIOLOGY	Botany Facility	EURECA
EXO BIOLOGY	Exobiology & Radiation Assembly	EURECA

TABLE 4.14 FACILITIES FOR THE PROPOSED EXPERIMENTAL
AREAS (source of data is document [6])

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4.5.3.3 Experiment Requirements

- Dimensions/Volume

The most demanding facilities among the considered ones are found to comply in any case with the Spacelab rack envelope; by consequence, a volume of about 1 m^3 should be sufficient for accommodating all the elements of any facility.

However, this value could be reduced by consideration of shifting part of the facility equipment to a "common electronics area", and, besides, the mean value of the engaged volume is lowered by the presence in the list of the "representative" facilities of many smaller modules homed on board EURECA or TEXUS/MASER (less than 0.5 cubic meters on the whole, while the typical dimension of the sheer experiment/processing chamber is assumed ≈ 0.1 cubic meters).

On the other hand, addition of diagnostics and dedicated visualization means can play a competitive role.

- Mass

The Ref. doc. [6] quotes the value of 50 Kg as the most effective estimator of the upper limit of an individual experiment core typical mass. This value is obtained considering that "lightweight" facilities comply in all cases with the previous limit, while the "heavy" ones can be decomposed so that their experiment core only is considered.

Indeed, some EURECA facilities range up to about 200 Kg and this value could be taken as a fair estimate of a maximum mass envelope, since it refers to a bulk of elements some of which are endowed with such capabilities as: automated sample processing and exchange, fully unmanned experiment operation.

This value may absorb opposite direction oscillations due, respectively, to re-design for mass savings and common equipment detachment and to additional diagnostics / data and image recording implementation.

Common equipment (including data/video memories) masses are not considered, obviously, in the previous mass budget item. However, the overall mass target for the Payload Module (≈ 1000 Kg) seems widely sufficient.

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• Data rate

The exact amount of real time interaction required during the evolution of the experiment is still to be defined. Substantially all the experiments with fluid, optically transparent phases (fluid dynamics, thermodynamics, combustion,...) and botany experiences require optical measurement and visualization means, while non transparent phases (solidification) do not need, even if infrared range information might be collected and could need transmission.

If a real time interactive role of users is looked for, images and data will need to be transmitted to the "telescientist" on board the Station or to the user ground bases, while if a fully preprogrammed set of runs is considered satisfactory (scientific data known and scientific return evaluated a posteriori), only a reduced set of data will be forwarded (monitoring, safety, selected physical data).

However, a basic estimation of the orders of magnitude of the data rates is obtained in spite of the already mentioned uncertainty factors. A distinction is made between telecommands and telemetry.

Due to the similarity with the Elevator as far as automatic/remote management of the experiments is concerned, EURECA design suggests to envisage a similar value for the Payload Module uplink bit rate.

Telecommands are intended to provide updating/replanning of operative sequences and possible unplanned modification of physical parameters value.

This leads to an order of magnitude of 1 Kb/s (not continuous over time), which is compatible with the baseline capability of the Elevator.

Concerning downlink, generation of both monitoring/housekeeping and science data is felt to range from some Kb/s up to some tenth of Mb/s (strongly depending on the presence of video cameras, the number of scientific data sources, measurement accuracy, sampling rate, etc..).

Of course, whenever the generated data rate exceeds the allocated transmission capability (≈ 100 Kb/s), only a selected portion will be sent to the ISS in real time, while an adequate amount of memory locations will be used to record the remnant of the experiment history (even as a temporary buffer for delayed downlink).

• Electric power

What is usually reported about facility power requirements is the maximum absorption value ("peak" power),

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since this is clearly identifiable as a design constraint.

On the contrary, an average (over time) power absorption (during operative phases) is less univocally defined, as it depends on the kind of experiment performed (many are possible with multiuser facilities) and on the kind of materials employed, duration, etc..

The former value is necessary to verify the maximum power level available at the resource interface, while the latter is necessary to check the amount of energy reserved by the carrier to experiment purposes.

Sometimes peak values are considerably higher than average ones. This is the case of the furnaces boarded on rockets, where a very high amount of power is employed at the beginning of the experiment to quickly melt the metallic sample in order to save the highest amount of the few minutes long experiment time.

The facilities considered in the mentioned review range up to 1000 W as a peak, while often "average" reference values are not reported, as they were not found.

However, it is felt meaningful to make the following assumptions:

- a) peak values are reasonably "short" respect to total operative time and peak coverage can be obtained by proper management of the supplied energy flux; in any case, peak "height" may be lowered by prolonging peak operation time (conservation of energy).
- b) "average" power values have to be considered to estimate the energy resources.

Some peculiar uncertainty factors influence the average power values, in addition to the general ones already mentioned (facility expected modifications, provision of additional equipment for diagnostics).

Anyway, as peak power values around 200 + 300 W are usually a limit for all the kinds of facilities, exception made for high temperature / high power furnaces, it is expected that corresponding average values can be estimated being not larger than few hundred of watts.

Entering values of this order of magnitude into power vs. mission duration diagram (Fig. 4.5-27), and taking into account that about 200 W are used for Service Module own power needs, it is possible to verify if solar array assisted battery package provision of energy is sufficient. Actually, a full mission time coverage (one month) is possible up to ≈ 400 W (P/L module portion), while an increase at ≈ 500 W would imply a maximum mission duration of 23 days.

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This first cut results look like satisfactory: hours- or day-long experiments are allowed to scan all their gravity bands with hundreds or tens of experimental runs; only experiments lasting many days or (up to 2) weeks may undergo a reduction of the maximum theoretical duration (one month) of the mission, one or more of which could be needed to explore all their bands. Incidentally, these latter classes are botany and crystal growth from vapor, whose power requests are not the higher ones.

• Rejected heat

The estimation of the P/L rejected heat load is made by supposing that it basically equals the electric power input (no refrigerators on board or, however, negligible energy removal at low temperature respect to overall heat loads).

Deviations from this situation may come only from heat released by chemical reactions (for instance: combustion experiments).

Under this hypothesis the maximum thermal output amounts to few hundreds of watts.

Combustion or quick quenching process hot gases can be vented, anyway, outside the Elevator, provided that they do not pollute significantly the surrounding environment.

• Environment

In general, all the experimental issues require an utmost attention to the setting, monitoring and control of the various physical parameters (so as it is possible to trace any experiment result back to its true cause, excluding the possibilities of uncertain paternity). This underlines the importance of thermal stability, cleanliness, etc.. in the P/L module.

A pressurized environment inside the Payload Module is not mandatory, and depends also on the modalities of the servicing operations (inside/outside the Space Station); however, adaptation of a part of the candidate facilities/ subunits is expected, as part of them are designed for pressurized (Spacelab) and part for unpressurized environment (i. e. rockets).

Life support is essential for experiments in botanic sciences: an internal pressurized environment is provided in botany facilities; however, this can be a facility provided feature, not a laboratory one.

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4.5.3.4 Payload Module Configuration Drivers

Payload Module(s) must be designed to fit into the space between the two platforms hosting the Service Module subsystems. This puts a limit of about 0.8 m on the overall height (dimension along the Z-axis) of the module, taking into account 0.1 m for the accommodation of the mechanical interface with the SM plus a clearance margin.

The extension of the Payload Module in the XY-plane, on the other hand, is mainly constrained by:

- 1) the "degradation" of the microgravity environment with the increase of the distance from the Elevator CM due to gravity gradient and attitude motion (Ref. chapter 4.1 of Quarterly Progress Report #6);
- 2) the presence of the tether and of the beam connecting the SM platforms;
- 3) the dimensions/volume of the payloads to be housed.

The mentioned requirements lead to assume as reference preliminary envelope of the Payload Module a 0.8 m height cylinder, with radius ranging between 1 and 1.5 m, and provided with slot 0.44 m wide (see Fig.4.5-29).

Payload Module is inserted into the SM so as to have its slot aligned to the SM slot (in other words, both slots lie on the same side). This configuration allows the Elevator to be detached from the tether without any previous PM dismantling.

The mass properties of the Payload Module must be so as the CM of the overall Elevator lies on the tether, and the principal axes of inertia are aligned with the Elevator reference frame axes to avoid the arising of disturbance torques both during transfer and station keeping phases.

The resultant volume of the Payload Module envelope is included between ≈ 2 and ≈ 5 cubic meters, and, even considering the possible reduction relevant to geometric constraints (surface different from circular cylinder), structure, thermal insulation, electronics, etc., should abundantly fulfil all the payload accommodation requirements.

In line of principle, the equipments to be mounted on

the Payload Module can be grouped in two categories:

- a) common equipment (electronics for gathering and sending the scientific/housekeeping data to the SM Data Handling Subsystem, electrical, electronic and mechanical interfaces, part of the thermal control), which is common to every payload and is the fixed part of the PM.
- b) experiment dependent equipment (experimental core equipment packages, sensors, diagnostics, visualization apparatuses, illumination systems, optical media such as optical beam elements, optical fibers, possible additional accelerometers, batteries, or mass memory, dedicated thermal control), which is generally to be exchanged mission by mission.

The latter should therefore be located in easily accessible places inside the Payload Module. The standard accelerometer package, provided to each payload, must be placed as close as possible to the experimental facilities.

A tentative layout of the PM is shown in Fig.4.5-30.

Note that in case radiating surfaces are needed to reject the heat produced by the experimental facilities, these must be placed on the rear (-Y) side of the module. In fact this is the only side which never receives direct sunlight during the course of the mission.

Payload Module walls are requested to provide thermal decoupling of the internal environment from the external one (Service Module included), to avoid light infiltration from outside, and to assure internal atmosphere containment (if any).

The mechanical interface between the two Elevator modules must allow an easy assembly/disassembly of the PM on the SM.

A possible solution consists in using guides mounted on the +Z or the -Z side, to be inserted into two guide rails placed on the corresponding side of the SM.

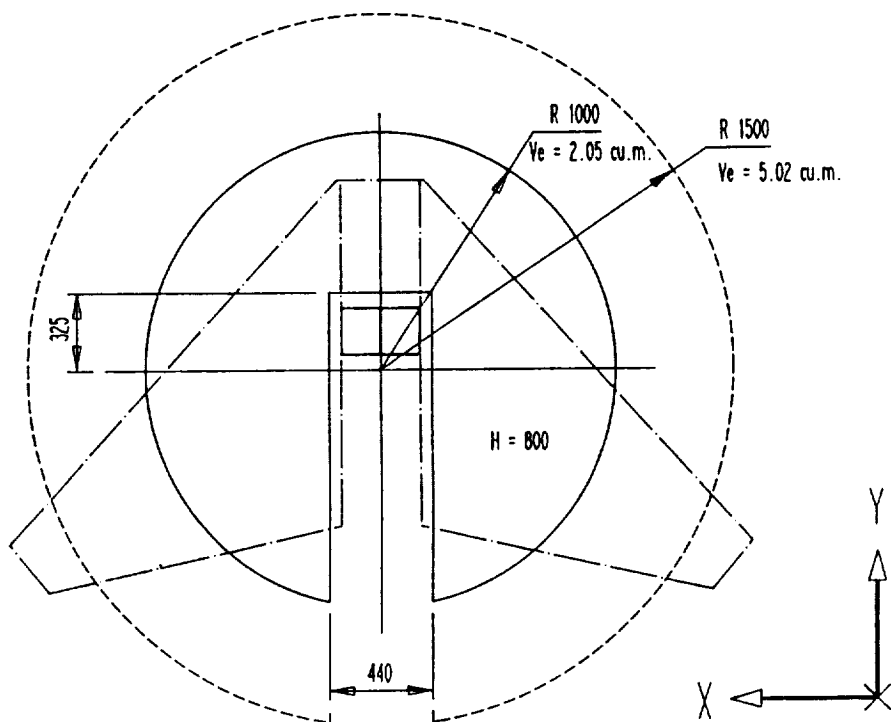


FIG. 4.5-29 PAYLOAD MODULE ENVELOPES

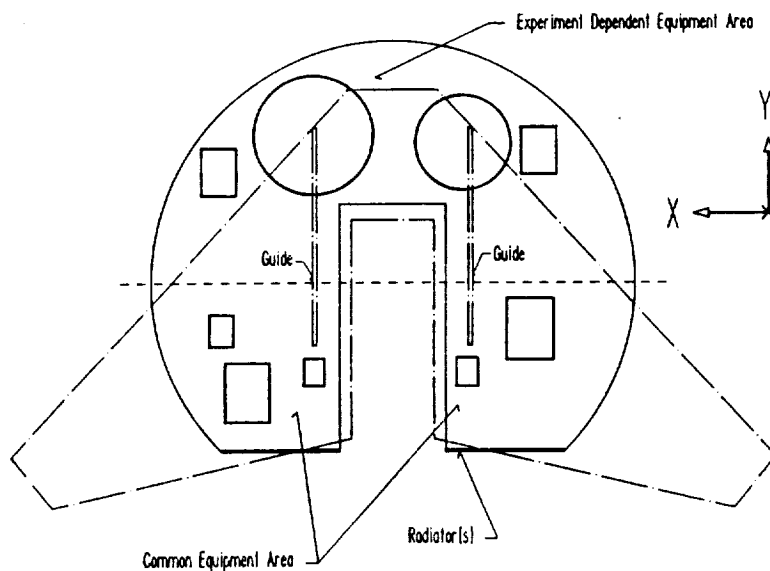


FIG. 4.5-30 TENTATIVE PAYLOAD MODULE LAYOUT

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4.6

SUMMARY AND RECOMMENDATIONS

The VGL Concept

The purpose of a Variable Gravity Laboratory (VGL) is to make available to the Space Station users a facility to perform experiments at a controllable and predetermined level of acceleration.

The way of achieving such a result lies in exploiting the gravity gradient acceleration field by means of a tethered system attached to the Space Station.

Placing the VGL on the tether at a proper distance from the Center of Gravity (CG) it would be possible to cover in a continuous manner a whole range of g levels. Furthermore it is conceptually possible to place the VGL exactly on the CG eliminating completely the gravity gradient effect.

The tether can also reduce the level of acceleration felt by the VGL due to the high frequency mechanical noise generated on the Space Station. So, in line of principle it is possible to reach a better microgravity quality on the VGL than on the Space Station laboratories.

VGL Utilization Scenario

The purpose of the present work has been to analyze the possibility of early implementation of the VGL and so the phase-1 Space Station configuration has been selected as baseline for analysis purposes.

In this scenario the VGL has to be seen as an added capability of the Space Station and has to be utilized only when required. So a VGL that is operated for a limited time has been devised, and a single tether system has been selected in order to limit the impact on the Space Station.

The VGL can be seen as a dual capability facility. The first capability is that of using the VGL as a Variable Gravity Laboratory (in the range 10^{-6} to 10^{-2} g). In this respect the VGL offers a unique capability which cannot be matched by any other facility. The second capability is the use of the VGL as a microgravity facility where the g quality could be

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better than the one obtainable on the Space Station retaining an easy access to all Space Station resources.

Seen as a microgravity payload, used only occasionally and for relatively short duration, the VGL would not be disruptive of the microgravity experiments on Station Laboratories being "the" microgravity experiment at that time.

The VGL System

A wide range of VGL configurations is possible many of which need at least some attention. The Elevator concept has been selected as more attractive facility for carrying the variable gravity experiments.

The Elevator is a space element that is able to move in a controlled way along a tether of constant length. A slot cuts the Elevator structure along its height in order to allow its hooking on the tether by means of a translation guide. The motion along the tether is controlled by two drive mechanisms placed externally at the top and bottom of the Elevator structure.

The experiments are housed in a payload module which can be mounted on the Elevator through proper mechanical and electrical interfaces. This solution has been preferred to simplify the operations required to replace payloads on the Space Station, and to increase flexibility as the constraints on the size of the experiments are greatly relaxed.

The VGL system is completed by a deployer system, to be mounted on the central bay of the Station transverse boom, and a ballast mass to be deployed at proper distance from the Station.

Further Elevator Applications

Beside the basic application as a VGL the Elevator system can be used in perspective for many other purposes which would enhance its value as possible Space Station facility. These are for instance:

- o Tethered Facilities Servicing.
The idea of using large tethered platforms connected to the Space Station makes unrealistic frequent operations of deployment and retrieval. On the other hand, the platform may require easy access for

maintenance, supply of consumables, module and experiments exchange.

The Elevator system used as a transportation facility, able to move along the tether to and from the platform, may be the necessary means for rapid transport replacing lengthy retrieval procedures and assuring quick intervention in the case of major failures.

- o Tether Inspection and repair.

A problem related to the use of long tethers in space concerns the tether survivability in an environment populated by a large amount of natural and artificial particles. A suitable external shield has to be foreseen to assure the tether survivability, nevertheless progressive damage has to be counteracted. Periodically, the Elevator could perform tether inspection missions both by visual and instrumental detection. When damage is detected, the specially equipped Elevator could be positioned near the damaged zone and could initiate activities necessary to repair the tether.

- o Danger avoidance.

Operations which could not be performed on the Space Station for the hazards involved could take place on the Elevator at a safe distance in a facility that could exploit the Space Station resources.

- o Reentry.

The Elevator's ability to move along the entire length of a deployed tether would allow subtle adjustments of the reentry trajectory of an attached reentry vehicle. This would result in fuel mass savings and, therefore, cost savings, for such a reentry vehicle which could be used for scientific, transportation and waste management applications.

- o Launch.

Payloads to be launched into higher orbit by the Orbit Transfer Vehicle need to be moved far from the Station. The Elevator may carry out this operation, moreover, the tether capability to act as a momentum transfer element can be exploited to aid the launch operations. The Elevator, because of its intrinsic capabilities, may be considered, in this application, as an active mobile launch platform.

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o **Rendezvous.**

High level disturbances could arise from the typical operation of docking of space vehicles on the Space Station. Thus, having a docking port far enough from the core Station would be desirable.

The Elevator positioned in the Center of Gravity of the system (lying along the deployed tether) could act as such a docking facility. Small vehicles, payloads and materials could be transferred and then transported to/from the Station by the Elevator.

Recommendations

The VGL peculiarities require a relevant level of analysis effort and technology development.

Therefore, a two step approach should be planned in order to gain insight in its critical areas and technological problems by means of a number of demonstrations both on-ground and in-flight.

The ground test activity purpose should be, from one side, validation of the motion control strategies utilizing refined computer simulations, to the other, verification of the drive mechanism performance both for the control of the along-tether motion, and of the radial pressure which is involved in the motion generation.

Other ground test objectives should be the verification of the Elevator/tether hooking-unhooking interfaces and operations, and the selection of suitable tether materials in order to optimize the interfaces of the drive mechanism with the tether.

The real capabilities of the VGL system can be demonstrated only in the space environment and as logical subsequent step a Shuttle demonstrative mission could be planned with the realization of a small Elevator model.

The VGL demonstration flight objectives should be to demonstrate the ability of VGL to move along the tether in a controlled way, by means of a suitable drive mechanism, and to measure the residual gravity field on board the VGL at different stations along the tether and during controlled motion.

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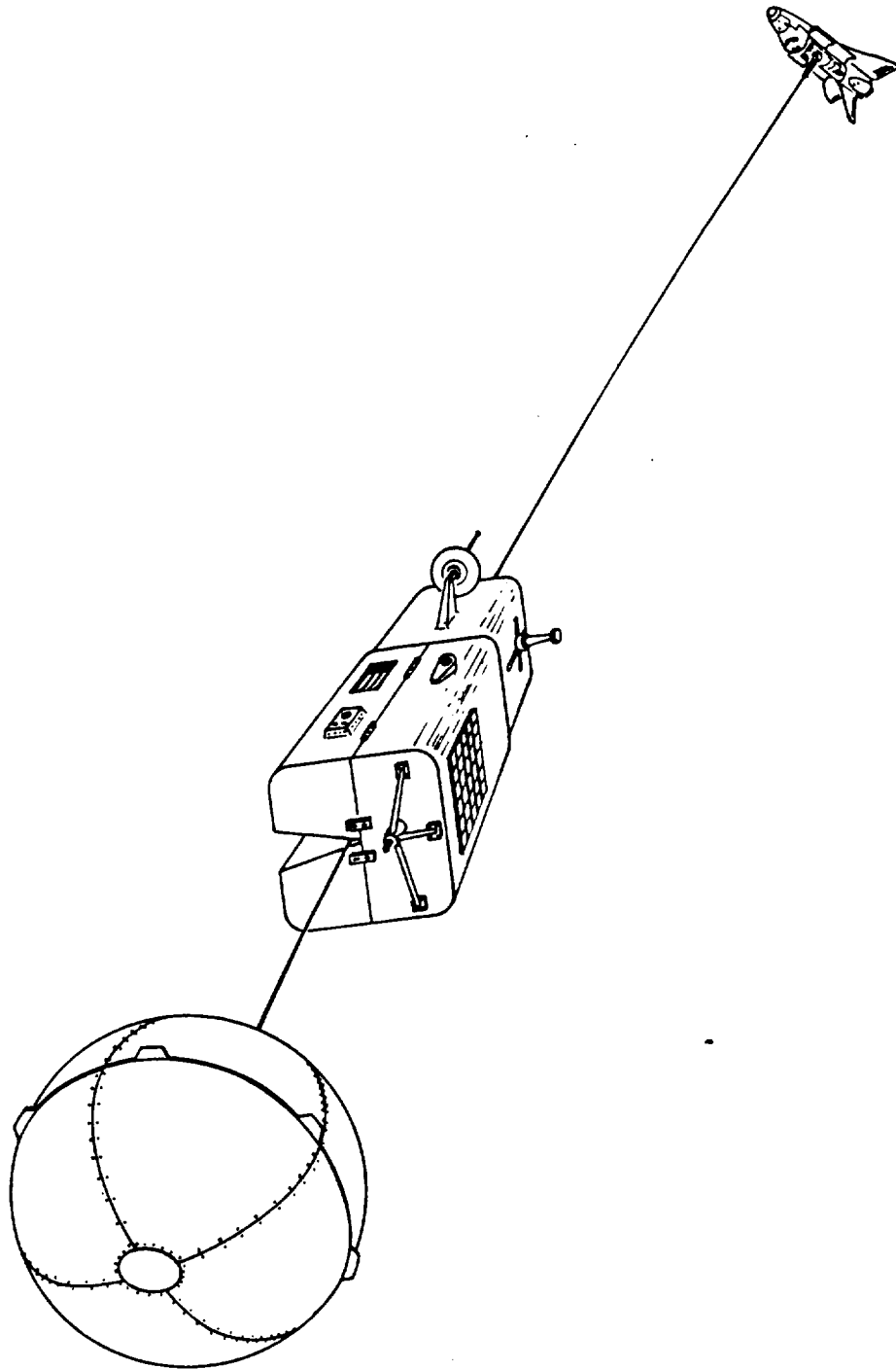


FIG. 4.6-1 THE ELEVATOR FLIGHT DEMONSTRATION

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The system proposed (see Fig.4.6-1) for the flight test of the VGL concept is made up of three major elements: a Deployer system, allocated into the Shuttle cargo bay, a tethered Satellite and the Elevator model.

As a general guideline it has to be considered that both cost and schedule constraints impose the necessity to reuse to the maximum possible extent the hardware under development. In particular the capability to control and to measure the system dynamics is required for the objective of the mission. The Tethered Satellite System (TSS) seems the unique existing system able to perform this demonstration without any significant design change. The only new hardware development required would be the Elevator model. As a consequence, the VGL demonstration flight could be scheduled in conjunction with one of the follow-up TSS flights.

At least four engineering experiment goals can be recognized:

- o Measurement of the residual acceleration behavior as function of time for several Elevator positions along the tether.
- o Measurement of the residual acceleration profile vs. time as response to a commanded profile by Elevator motion control.
- o Measurement of the system dynamic response to the Elevator controlled motion from the Orbiter to the TSS Satellite.
- o Measurement of technical performance of the drive mechanism and of the transfer control techniques.

Design and development of VGL facility seems attractive due to the potentiality of this concept. It requires that the Space Station "makes room" for this possibility, and it requires that a number of technological problems are solved.

The study reported here is only a first step towards that goal. As essential steps along the way of VGL development, both laboratory tests and in orbit tests are needed. All that seems essential for the exploiting the maximum benefits from a Space Station architecture including tethers.

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SECTION - 5

ATTITUDE TETHER STABILIZER

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5.1 INTRODUCTION

The change of the baseline configuration of the Space Station from the Power Tower to the Dual Keel has been shown to be advantageous in many respects, including lower μ -g levels in the scientific laboratories and better visibility of both Earth and Sky.

From the point of view of attitude stability and control, however, it seems that things are going worse, because of the unfavorable inertia distribution of the Dual Keel with respect to the Power Tower.

To be more specific, let us consider the Phase-1 Space Station, when the assembling is completed and the configuration is no longer subject to further changes. Considering the International Space Station (ISS) as a rigid body and using standard stability techniques, it is easy to see that the inertia ratios are such that the ISS attitude is unstable in roll-yaw and even in pitch with respect to the gravity gradient torque. This means that the Control Moment Gyros (CMG's) have to be sized not only to balance relatively small perturbing torques, but also gravity gradient itself.

In addition the physical properties of the Station indicate that this configuration is very sensitive in pitch to atmospheric drag. A four meter offset between the center of pressure and the center of gravity causes an aerodynamically induced positive torque about the pitch axis.

This situation is far from favorable and appears to be a serious penalty paid to the advantages of the scientific experiments mentioned above.

Now, it is evident that the CMG's stabilization of a body with the dimension and mass of the ISS is not a major technological problem, but the fact that gravity gradient is not a friend poses the serious problem to find other means to reach attitude stability, above all considering potential failures of the primary Attitude Control System (ACS).

These means should be passive, or semi-passive, both for simplicity and relatively low cost, and also to minimize the dynamic noise in the scientific laboratories. In this respect, information is lacking (and needed) about

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the spectrum of the noise originated by the CMG's and filtered by the ISS structure.

Thus, the purpose of this study is to investigate the stabilizing effect of one of these means, i.e. of ballast masses tethered to the ISS in such a way to produce additional gravity gradient torques.

5.2 SPACE STATION REFERENCE CONFIGURATION

In this chapter we outline what are the basic characteristics of the Space Station for what attains the attitude control problem. As an important premise it has to be said that we relied on a minimum of rough information (from Ref.[7]) and on their logical consequences.

5.2.1 REFERENCE STATION PHYSICAL PROPERTIES

The phase-1 Space Station configuration is shown in Fig.5.2-1. The Station structure consists of a transverse boom which supports the pressurized modules, a photovoltaic power system, and a thermal radiator system. The four modules are located at the center bay of the transverse boom. Tracking of the solar vector by the power generation system is provided by two sets of gimbals.

The assumed physical properties are shown in Table-5.1. The orbital reference frame is oriented with the Z axis along the local vertical toward Earth, the X axis along the orbital velocity and the Y axis pointing the pole of the orbit. The nominal flight configuration presents the long transverse boom aligned with the Y axis, therefore perpendicular to the orbital plane. A Torque Equilibrium Attitude (TEA) flight mode is required in order to balance the aerodynamic torque about the pitch axis, resulting in a large pitch angle.

The physical properties also indicate a misalignment of the principal inertia axes with respect to the orbital reference frame and the large drag-exposed area due essentially to the solar arrays.

5.2.2 REFERENCE ATTITUDE CONTROL SYSTEM

The Space Station attitude control is provided by a combination of Control Moment Gyros (CMG's) and chemical Reaction Control System (RCS) thrusters.

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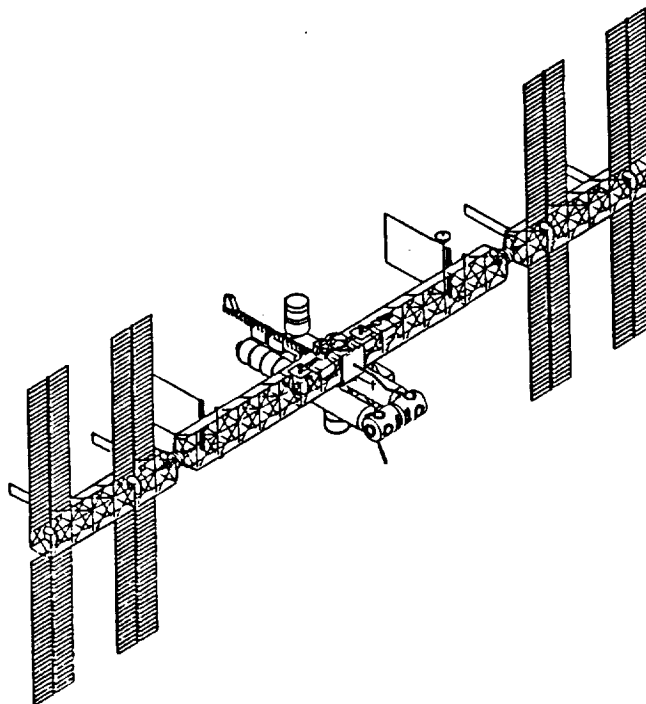


FIG. 5.2-1 REFERENCE SPACE STATION CONFIGURATION

ALTITUDE = 352 KM	MASS = 219000 KG	DRAG AREA = 2169 M**2
CD = 2.3	M/CD*A = 44 KG/M**2	
INERTIAS (KG*M**2)		
IXX = 9.08 E+7	IYY = 2.54 E+7	IZZ = 1.05 E+8
IXY = 1.12 E+6	IXZ = -1.62 E+6	IYZ = -5.52 E+5
PRINCIPAL AXIS (DEGREES)		
PSI(Z) = 1	THETA(Y) = -6.27	PHI(X) = 0.31
C.G. LOCATION RESPECT TRUSS CENTER (M)		
X = -3.16	Y = 0	Z = 3.36
CENTER OF PRESSURE RESPECT TO C.G. (M)		
X = 0	Y = -0.3	Z = -3.5
TORQUE EQUILIBRIUM ATTITUDE (DEGREES)		
PSI(Z) = 1.54	THETA(Y) = -15.52	PHI(X) = 0.4

TABLE 5.1 SPACE STATION REFERENCE PHYSICAL PROPERTIES

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5.2.2.1 Control Moment Gyros

Six CMG's are located in the transverse boom near the module cluster. The CMG's proposed are a double gimbal design with a nominal angular momentum absorption of about 5000 N·M·S and with a maximum torque of about 1600 N·M when used in combination about a single axis. The CMG's are the primary effectors as momentum exchange devices during steady-state operations. They need to be periodically off-loaded by the RCS and probably should be inhibited during orbit reboost, collision avoidance, and large disturbances maneuvers.

5.2.2.2 Reaction Control System

The RCS consists of four pods, with two pods located near each end of the transverse boom. The RCS design consists of 18 thrusters with thrust level of about 100 N as order of magnitude. The roll-yaw control moment arm is about 30 m and the pitch moment arm is estimated to be about 3 m. The RCS thrusters are used for CMG's off-load, orbital reboost and as an auxiliary attitude control system in the case of CMG's inhibit or failure.

5.2.2.3 RCS Propellant Tank Farm

To implement RCS functions a hydrogen-oxygen system is utilized which provides a specific impulse of about 380 seconds. Water is scavenged from the Orbiter fuel cells. An electrolyzer is utilized on board the Station to decompose the water back into hydrogen and oxygen and stored for use as propellant. The Station can generate fuel at a rate of about 22 Kg/Day. Current design sizing utilizes on board propellant storage tanks that have a capacity of about 1500 Kg, and two storage tanks for water that have a total capacity of 1800 Kg. The water is scavenged from the Orbiter at a rate of 600 Kg for flight.

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5.3 STATION ATTITUDE CONTROL FEATURES

The Space Station inertia properties result in a spacecraft that is unstable in a free drift flight mode. This means that the Space Station is not able to maintain stable attitude librations around flight attitude if it is not actively controlled. In fact the inertias relationships are:

$$I_{yaw} > I_{roll} \gg I_{pitch}$$

which result in instability in pitch and a large instability in roll-yaw that are coupled.

Another problem is the impossibility, with a reasonable CMG's sizing, to maintain the Local Vertical Local Horizontal (LVLH) attitude flight mode that would be desirable for payload pointing requirements. In fact the high drag torque about the pitch axis results in a large secular and control momentum buildup that would soon saturate the CMG's for a LVLH flight mode.

The only flight mode allowed is the Torque Equilibrium Attitude (TEA). The Space Station assumes a pitch orientation able to reduce at a minimum the environmental torques, balancing aerodynamic torques by gravity gradient torques. This results in a large pitch equilibrium angle. The CMG's are required to compensate variations of the environmental torques along the orbit, and even in TEA they require to be off-loaded approximately once per orbit by RCS.

5.3.1 NOMINAL TEA FLIGHT MODE

Assuming a linearized form of Station dynamics, the Torque Equilibrium Attitude in pitch is given by:

$$3 \cdot n^2 \cdot (I_{yaw} - I_{roll}) \cdot \sin \theta = 0.5 \cdot C_d \cdot A \cdot \delta \cdot V^2 \cdot Z_p \cdot \cos \theta$$

where:

n = mean orbital motion
 θ = pitch angle
 C_d = drag coefficient
 A = drag area assumed constant along the orbit
 δ = atmospheric density

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V = orbital velocity
Z_p = shift along Z axis of center of pressure respect
to the CM

Utilizing the Station physical properties shown in Table-5.1, and assuming an average atmospheric density of $2.7 \cdot 10^{-11}$ Kg/m³ the TEA pitch angle results about 15.5 degrees. The TEA around roll and yaw are quite smaller as can be seen from Table-5.1. It has to be outlined that this static equilibrium is intrinsically unstable. In fact, the smallest perturbation is able to push away the Station from the TEA condition.

The atmospheric density is expected to vary along an orbit for the effect of the day/night heating and cooling.

The CMG's are used to absorb the peak angular momentum due to the environmental torque disturbances when attitude is maintained at average TEA. Since the density along the flight path varies from orbit to orbit, TEA attitude orientation has to be adjusted periodically. Moreover the secular momentum buildup over the orbit has to be counteracted by the Reaction Control System.

With the assumption of a constant Station drag area along the orbit, the Fig.5.3-1 shows the atmosphere density and the pitch equilibrium angle vs. the true anomaly of an orbit. The pitch equilibrium angle ranges from about -12 to -17 degrees around the average TEA of about -15 degrees.

The pitch torque required to maintain the average TEA or an offset in the range -2 to +2 degrees from average TEA is shown in Fig.5.3-2 vs. true anomaly. The required pitch torques are comparatively small but the maximum control momentum is quite large as it can be seen in Fig.5.3-3.

Moreover it is evident what happens in the case of shift from optimal average TEA; the secular momentum buildup along the orbit increases dramatically. Notice that in the real case and even for average TEA, a secular momentum buildup (comparatively small) is present and RCS thrusters have to be periodically used for CMG's off-load.

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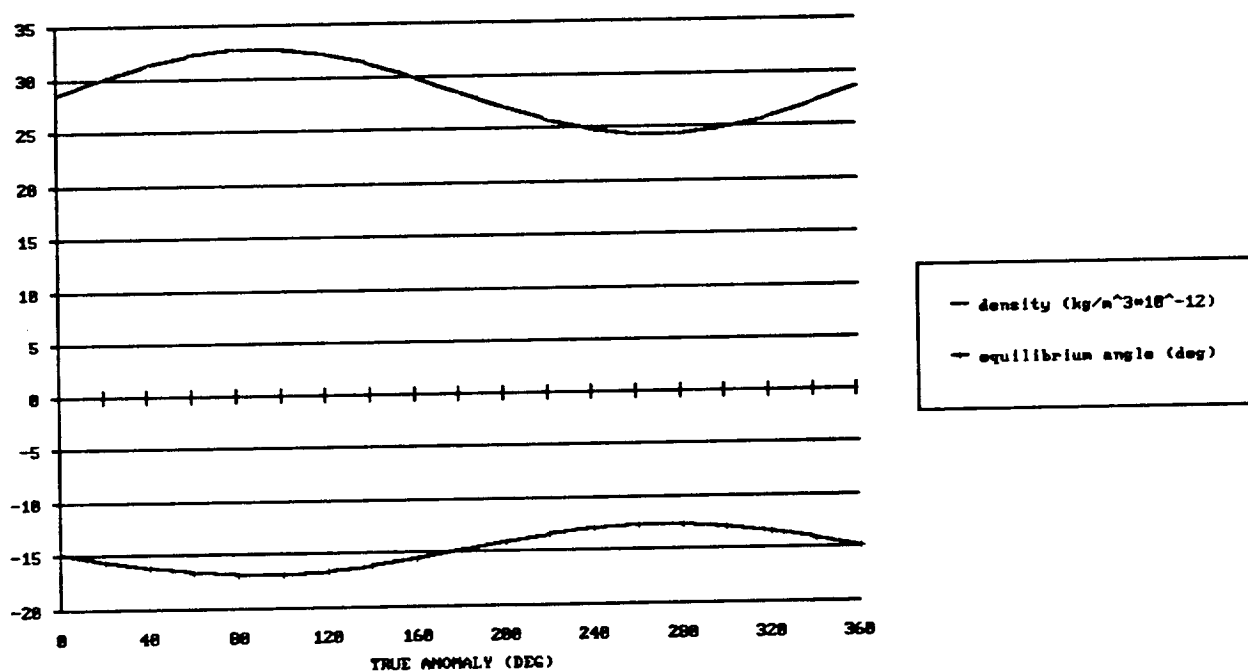


FIG. 5.3-1 ATMOSPHERE DENSITY AND PITCH EQUILIBRIUM ANGLE
VS. TRUE ANOMALY

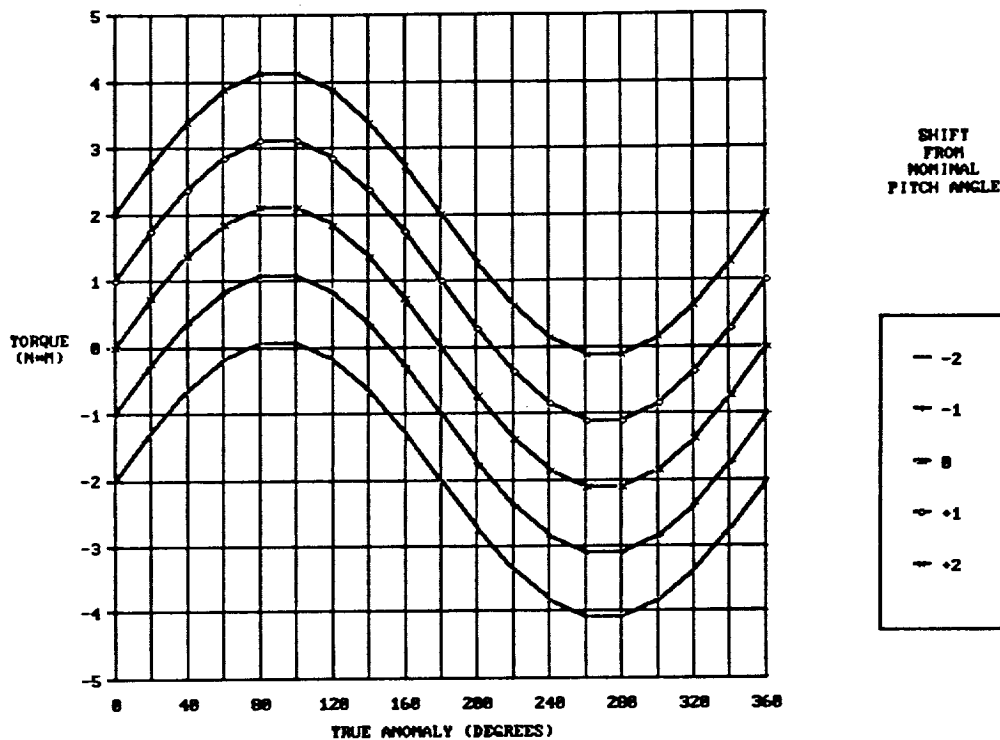


FIG. 5.3-2 REQUIRED PITCH CONTROL TORQUES

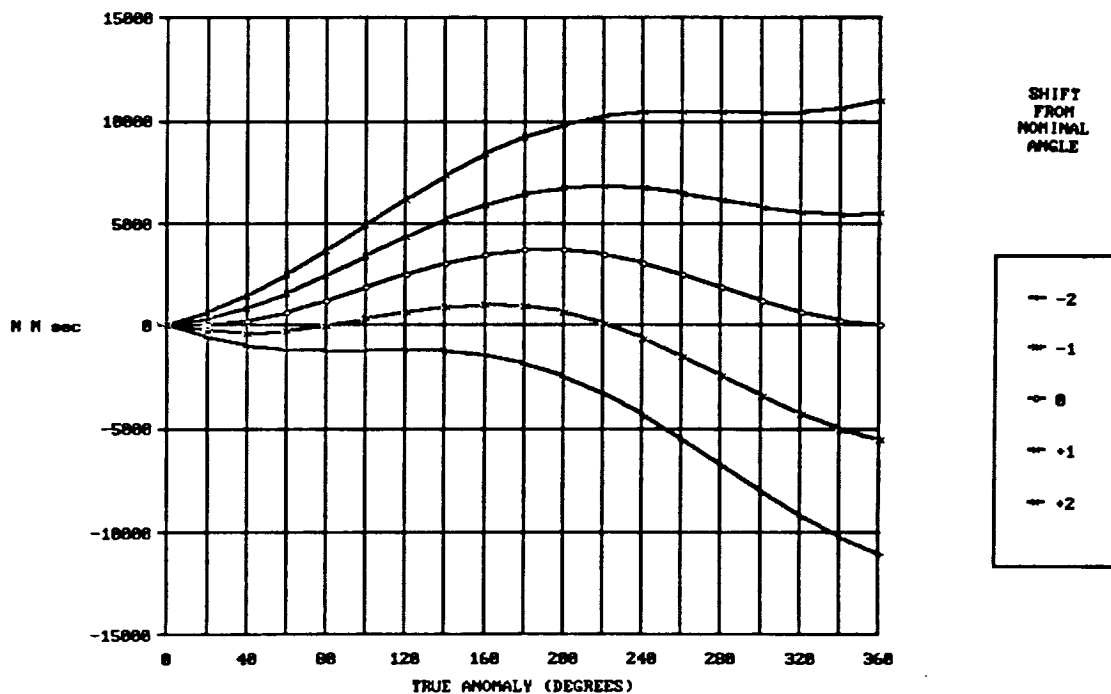


FIG. 5.3-3 CONTROL MOMENTUM AT TEA AND FOR OFFSETS FROM TEA

5.4 PRELIMINARY ANALYSIS OF STABILITY

The addition of a tethered ballast constrained on the Space Station on a point different from the Center of Mass (CM) has a deep impact on the static and dynamics of the system.

In the following it is assumed that the tether attachment point is on a point at distance d from the center of mass along the local vertical.

5.4.1 STATIC EFFECTS

Two are the main effects of the tether system:

- a) Tether tension causes a restoring torque when the pitch angle is made to be different from zero. The restoring torque is given by:

$$C = T \cdot d \cdot \sin(\theta)$$

where T is the tether tension. Tether tension is approximately given by:

$$T \approx 3 \cdot n^2 \cdot (M_b + 1/2 \cdot M_t) \cdot L$$

where:

M_b = ballast mass
 M_t = tether mass
 L = tether length

This torque can be made as large as desired with proper tether length and ballast mass sizing. When the tether system is added the resulting equilibrium angle changes, and can be made quite near to the local vertical. An useful parameter which gives an overall idea of the tether tension effect is:

$$I_d = M_b \cdot d \cdot L$$

which has the dimension of an inertia moment. To give an idea of the size of the things we are talking, to get a value of $I_d \approx 10^8$ we can use:

$d = 10 \text{ m}$
 $L = 6000 \text{ m}$
 $M_b = 1700 \text{ Kg}$

The equilibrium around the pitch axis is given then by:

$$3 \cdot n^2 \cdot (I_{yaw} - I_{roll} + I_d) \cdot \sin(\theta) = C_d \cdot A / 2 \cdot \delta \cdot v^2 \cdot Z_p \cdot \cos(\theta)$$

The resulting pitch equilibrium angle for various values of I_d is shown in Fig.5.4-1 (using the average value of δ).

It can be clearly seen that the pitch equilibrium angle can be kept within few degrees from the local vertical with reasonable values of I_d .

Another point worth to mention is the fact that the effect of changes in the atmospheric density can be reduced to a value as small as desired increasing the size of the tether system. In Fig.5.4-2 the trend of the equilibrium pitch angle along the orbit is reported (compare with the plots in Fig.5.3-1).

In conclusion it appears that the use of a passive tether to reduce the effects of atmospheric drag is quite effective.

- b) The presence of a single tether shifts the center of mass of the overall system increasing the level of residual gravity within the laboratories.

With I_d ranging from $50 \cdot 10^6 \text{ Kg} \cdot \text{m}^2$ to $100 \cdot 10^6 \text{ Kg} \cdot \text{m}^2$ and d in the range from 5 to 20 m, the shift of Center of Gravity (CG) is of the order of 10 to 100 meters. This shift can be translated in an increase of the background g level of the order of 3 to 30 μg ($10^{-6} g$) as shown in Fig.5.4-3. Two ways are possible to decrease the background g level (for a given value of I_d):

I) Increasing the value of d

II) Using two tethers deployed in opposite directions

A third effect due to the tether is present, that is the area increase due to tether and ballast. It is easy to see that the additional area is of the order of few m^2 , negligible in comparison to the overall area.

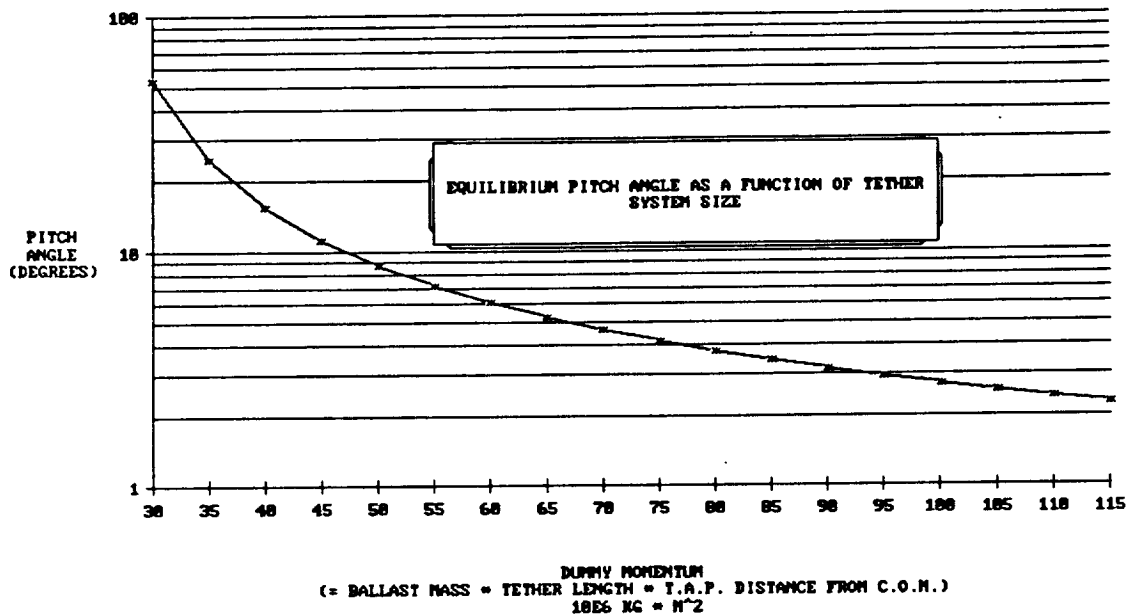


FIG. 5.4-1 EQUILIBRIUM PITCH ANGLE

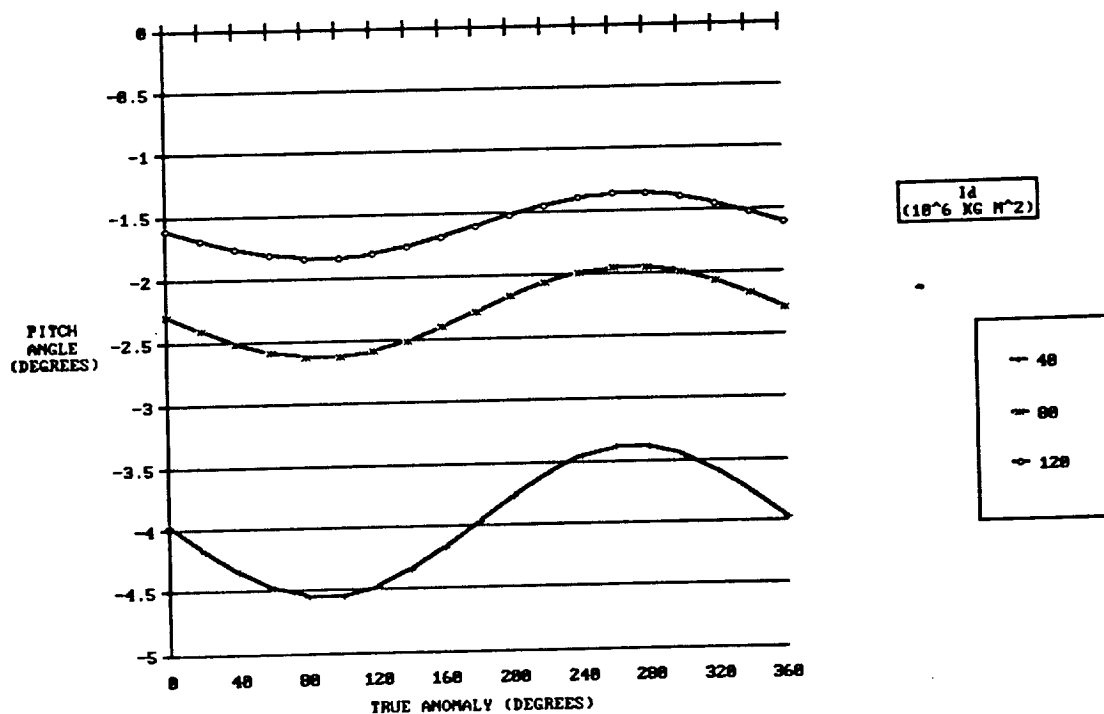


FIG. 5.4-2 EQUILIBRIUM PITCH ANGLE TREND ALONG THE ORBIT

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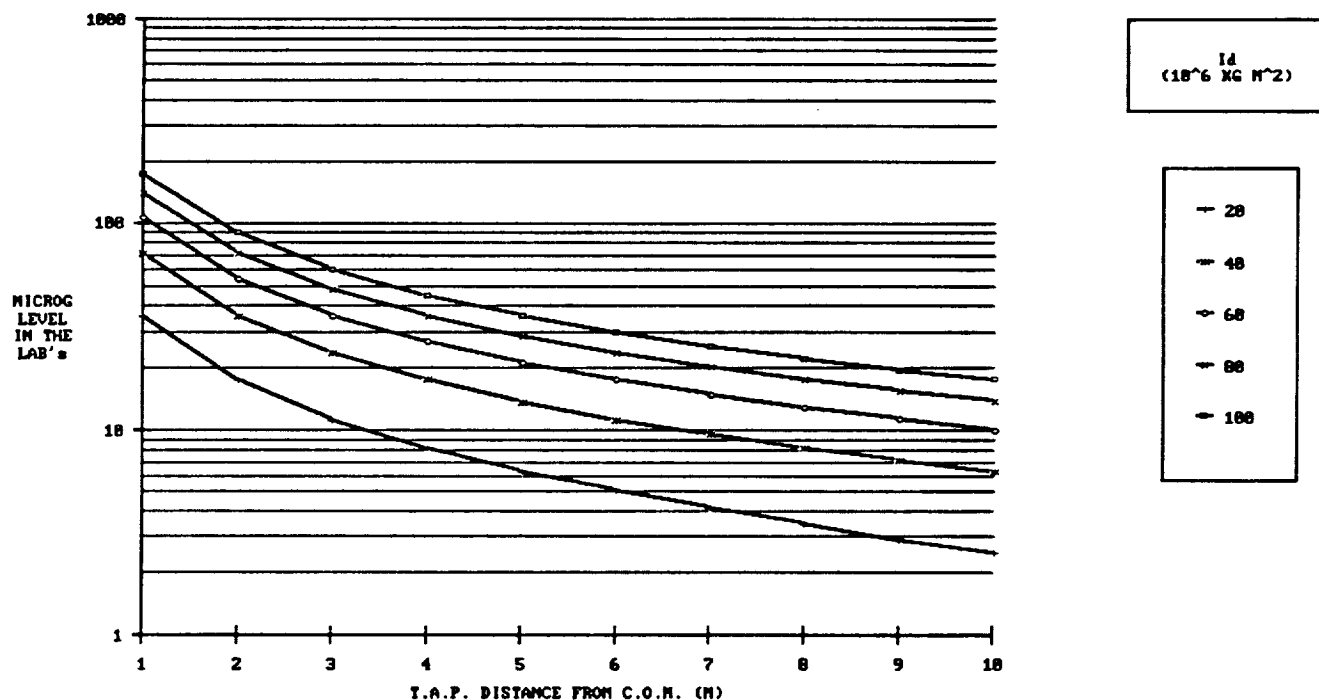


FIG. 5.4-3 EFFECT OF TETHER SYSTEM ON MICRO-G LEVEL

5.4.2 TETHERED SPACE STATION DYNAMIC STABILITY

Over the effect on the static of the system, the tether influences also the attitude dynamics.

5.4.2.1 Mathematical Background

The linearized equations leading the attitude dynamics of a generic body (spinning at a rate n around its pitch axis) are reported below:

PITCH EQUATION

$$I_p \ddot{\theta}_p = 0$$

ROLL EQUATION

$$I_r \ddot{\theta}_r + n (I_r + I_y - I_p) \dot{\theta}_y + n^2 (I_p - I_y) \theta_r = 0$$

YAW EQUATION

$$I_y \ddot{\theta}_y - n (I_r + I_y - I_p) \dot{\theta}_r + n^2 (I_p - I_r) \theta_y = 0$$

with:

I_p = pitch inertia moment
 I_r = roll inertia moment
 I_y = yaw inertia moment
 θ_p = pitch angle
 θ_r = roll angle
 θ_y = yaw angle

It is assumed that the principal axes are aligned with the pitch, roll and yaw axes.

From the start we concentrate on analyzing only the roll-yaw equations which are decoupled from the pitch one.

What we want to investigate is the stability of the motion. Basically what we do is to find out the eigenvalues of the matrix shown in Table-5.2 and to verify that the real part of the roots is zero (meaning that there is not an exponential growth of the affected angle).

To simplify the discussion we can use, instead of the values of I_p, I_r and I_y , the three parameters K_p, K_r and K_y where:

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$$s := \frac{s}{n}$$

Pitch equation	$\begin{bmatrix} s^2 \cdot I_p & 0 & 0 \\ 0 & s^2 \cdot I_r + \begin{bmatrix} I_p & -I_y \\ I_y & I_p \end{bmatrix} & s \cdot \begin{bmatrix} I_p & -I_p & -I_r \\ I_y & I_p & I_r \end{bmatrix} \\ 0 & -s \cdot \begin{bmatrix} I_p & -I_p & -I_r \\ I_y & I_p & I_r \end{bmatrix} & s^2 + \begin{bmatrix} I_p & -I_r \\ I_p & I_r \end{bmatrix} \end{bmatrix}$
Roll equation	
Yaw equation	

TABLE 5.2 FREQUENCY MATRIX OF A SPINNING BODY

Pitch equation	$\begin{bmatrix} s^2 & 0 & 0 \\ 0 & s^2 + K_r & s \cdot \begin{bmatrix} 1 - K_r \\ 1 - K_r \end{bmatrix} \\ 0 & -s \cdot \begin{bmatrix} 1 - K_r \\ 1 - K_r \end{bmatrix} & s^2 + K_y \end{bmatrix}$
Roll equation	
Yaw equation	

TABLE 5.3 PARAMETERIZED FREQUENCY MATRIX OF A SPINNING BODY

$$\begin{aligned}K_p &= (I_r - I_y)/I_p \\K_r &= (I_p - I_y)/I_r \\K_y &= (I_p - I_r)/I_y\end{aligned}$$

Given the physical meaning of I_p, I_r and I_y the values of the K 's are always bracketed within the range -1 and 1. In Fig.5.4-4.a the relationship between the values of K_r, K_y and the inertia distribution of the body is shown. Using this parameterization the frequency matrix becomes the one reported in Table-5.3. It is easy to see that the only condition needed to assure stability around roll-yaw is:

$$K_y K_r > 0$$

This is a known result saying that the spin axis has to be the either the minimum or maximum inertia axis. A pictorial representation of this result is shown in Fig.5.4-4.b.

Let us now consider the effect of gravity gradient only (local vertical along the yaw axis). From the expansion of the gravity field expression one can derive the equations reported below:

PITCH EQUATION

$$I_p \ddot{\theta}_p = -3 \mu/R^3 (I_r - I_y) \theta_p$$

ROLL EQUATION

$$I_r \ddot{\theta}_r = -3 \mu/R^3 (I_p - I_y) \theta_r$$

YAW EQUATION

$$I_y \ddot{\theta}_y = 0$$

In this case only the roll and pitch degrees of freedom are affected. Restricting our scope to the yaw and roll axes the stability condition is:

$$K_r > 0$$

and the relevant stability diagram is the one shown in Fig.5.4-4.c.

Finally in the general case of the Earth-pointing satellite in circular orbit the relevant equations are those reported below (the gravity field and the orbital rate are related by the relationship $\mu = n^2 R^3$).

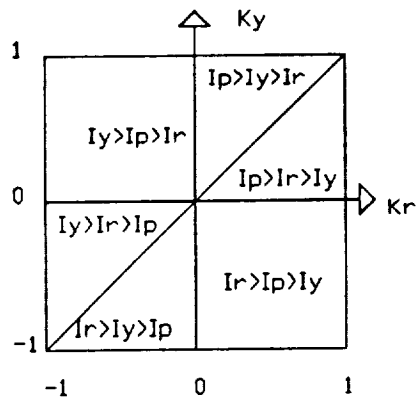


Fig. .a Meaning of
Ky and Kr

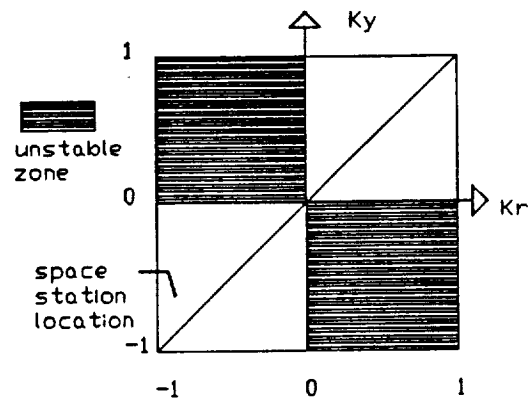


Fig. .b Spinning body
stability diagram

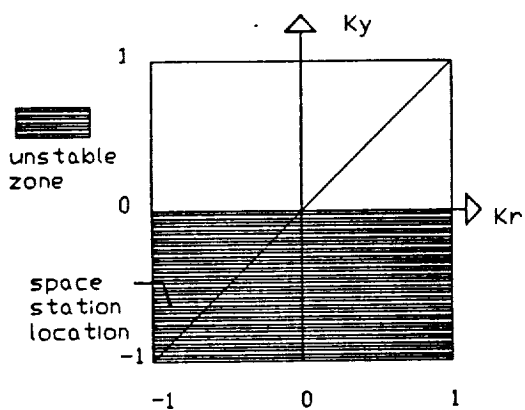


Fig. .c Gravity field
stability diagram

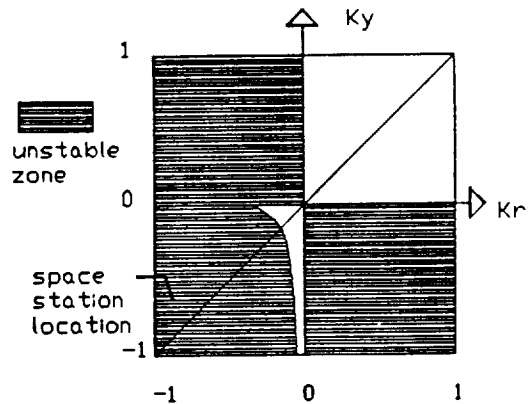


Fig. .d Earth pointing
orbiting satellite
stability diagram

PITCH EQUATION

$$I_p \ddot{\theta}_p = -3 n^2 (I_r - I_y) \theta_p$$

ROLL EQUATION

$$I_r \ddot{\theta}_r + n (I_r + I_y - I_p) \dot{\theta}_y + 3 n^2 (I_p - I_y) \theta_r = -n^2 (I_p - I_y) \theta_r$$

YAW EQUATION

$$I_y \ddot{\theta}_y - n (I_r + I_y - I_p) \dot{\theta}_r + n^2 (I_p - I_r) \theta_y = 0$$

From the equations it can be seen that if and only if the principal axes are aligned with the rotating reference frame the equilibrium is possible.

The stability conditions for the roll-yaw then become:

$$\begin{aligned} K_r K_y &> 0 \\ 1 + 3 K_r + 3 K_r K_y &> 0 \\ (1 + 3 K_r + 3 K_r K_y)^2 &> 4 K_r K_y \end{aligned}$$

The stability diagram is then the one reported in Fig.5.4-4.d. Notice that this diagram is not the simple superposition of the ones in Fig.5.4-4.b and Fig.5.4-4.c. In fact there is a stability region where the stabilizing gyroscopic forces prevail over the instability due to the pure gravity field effect. The Space Station position in the diagram is reported and its stability problem is apparent.

5.4.2.2 Tether Stabilizing Effect

What happens when there is a tether attached to the Space Station ?

The general discussion of the problem is extremely complex, but with a few simplifying assumptions, meaningful conclusions can be drawn.

The assumptions are:

- 1) The tether motion is not affected by the motion of the Space Station.
- 2) The distance between the Tether Attachment Point (TAP) and the Space Station CM is negligible when compared to the Space Station leading size.
- 3) The shift of the system CM is small when compared to the tether length.

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With these assumptions, only the static restoring torque due to tether needs to be included in the attitude equations.

As previously shown the tether tension gives rise to a restoring torque which is approximately given by:

$$C = T d \sin(\theta)$$

where T is the tether tension. Tether tension is approximately given by:

$$T \approx 3 n^2 (M_b + 1/2 M_t) L$$

With the further assumption that the tether mass is negligible and naming:

$$I_d = M_b d L$$

the complete dynamic equations are those here reported:

PITCH EQUATION

$$I_p \ddot{\theta}_p = -3 n^2 (I_r - I_y + I_d) \theta_p$$

ROLL EQUATION

$$I_r \ddot{\theta}_r + n(I_r + I_y - I_p) \dot{\theta}_y + 3n^2 (I_p - I_y + I_d) \theta_r = -n^2 (I_p - I_y) \theta_r$$

YAW EQUATION

$$I_y \ddot{\theta}_y - n (I_r + I_y - I_p) \dot{\theta}_r + n^2 (I_p - I_r) \theta_y = 0$$

The new roll-yaw stability conditions are:

$$\begin{aligned} (4 K_r + 3 r) K_y &> 0 \\ 1 + 3 K_r + 3 K_r K_y + 3 r &> 0 \\ (1 + 3 K_r + 3 K_r K_y + 3 r)^2 &> 4 (4 K_r + 3 r) K_y \end{aligned}$$

with:

$$r = I_d/I_r$$

For increasing values of r the new stability diagrams are those shown in Fig.5.4-5.a,.b,.c,&.d. It can be seen that the effect of increasing the tether length can be translated in a shift of an enlarged stability window where the stabilizing gyroscopic forces are greater than those due to gravity.

For the reference Space Station the two boundary values of I_d/I_r are:

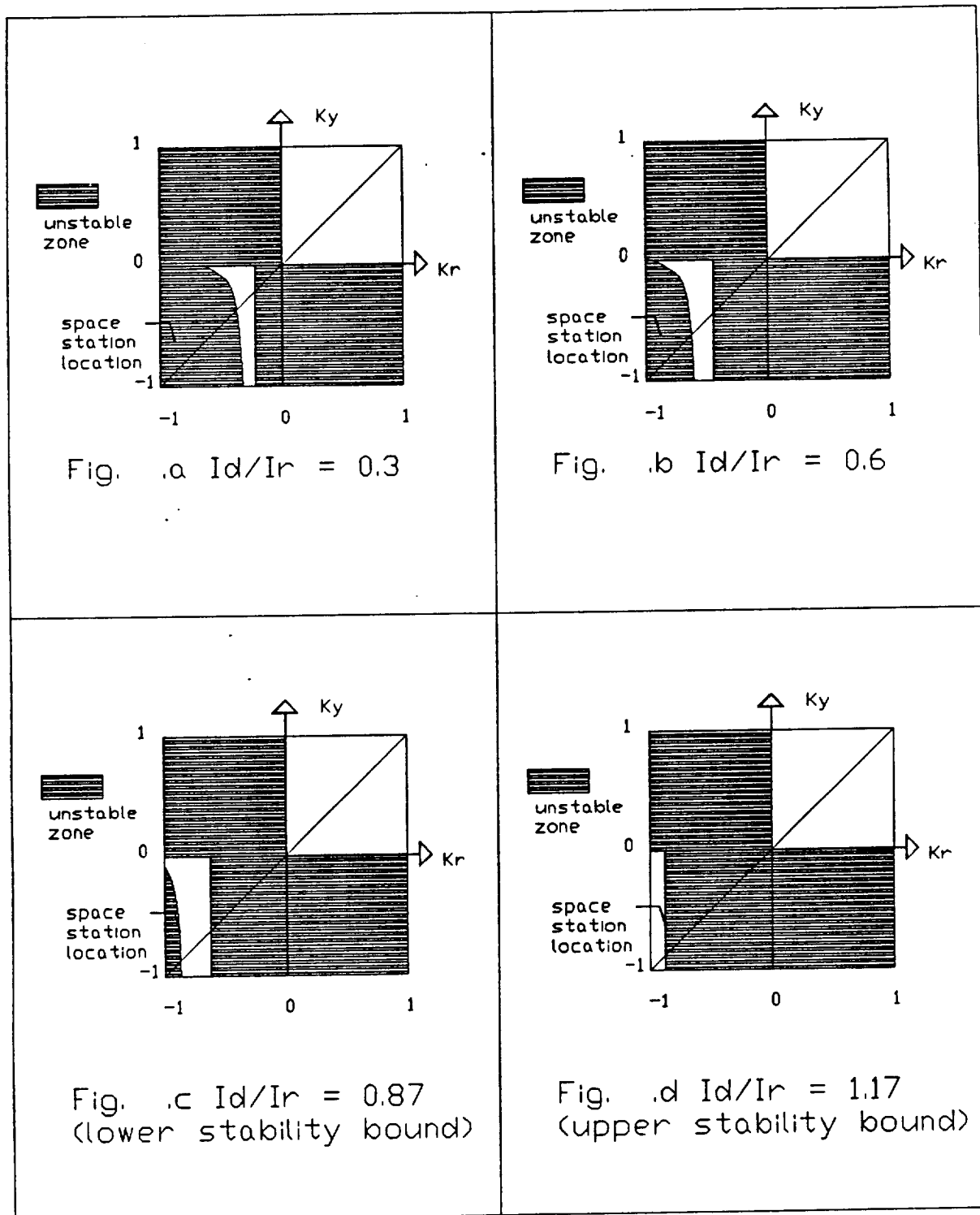


FIG. 5.4-5 TETHERED SPACE STATION STABILITY DIAGRAM

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$$1.17 > I_d/I_r > 0.87$$

that is:

$$10.6 \cdot 10^7 \text{ Kg m}^2 > I_d > 7.9 \cdot 10^7 \text{ Kg m}^2$$

The relevant stability diagrams for the two limit cases are reported in Fig. 5.4-5.c and 5.4-5.d.
The pitch motion is stable if the value of $K_p + I_d/I_p$ is greater than zero (see the pitch equation).
This happens for:

$$I_d > 1.42 \cdot 10^7 \text{ Kg m}^2$$

So if the system is stable in roll-yaw it is also stable in pitch.

In the prescribed range of values of I_d it is possible to find the natural frequencies of the attitude motion which are reported in Fig.5.4-6.

5.4.2.3 Remarks

Within the set of assumptions that we have made, we can say that it appears possible to achieve stability around the pitch and the roll-yaw axes. Notice that the tether has a direct stabilizing effect only on pitch and roll whereas the stabilization around yaw is achieved only exploiting the roll-yaw coupling due to centrifugal forces. Non linearities and/or the effects of neglected quantities require to be further investigated in order to validate this preliminary result on tether stabilizing effectiveness.

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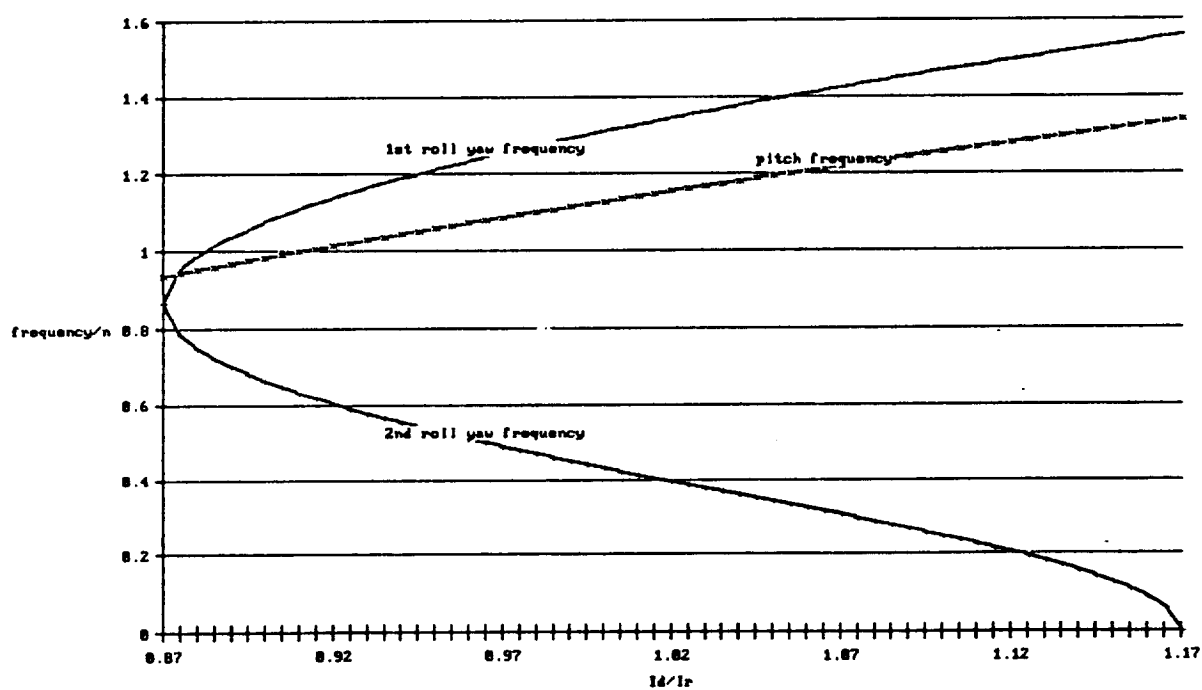


FIG. 5.4-6 ROLL-YAW AND PITCH FREQUENCIES AS A FUNCTION OF I_d/I_r

5.5 ATTITUDE TETHER STABILIZER

As shown in the previous chapter, it appears possible to achieve stability around pitch and roll-yaw axes in a passive way by a proper tether system.

The purpose here is to investigate the use of one or more masses tethered to the Space Station in order to aid the Attitude Control System of the Station.

5.5.1 STABILIZER CONCEPTS

Basically two stabilizer concepts can be envisaged as stabilization aid in the phase-1 Space Station scenario:

- 1) A permanent tether stabilizer to be considered as an integral part of the Attitude Control System and designed to alleviate the present CMG's requirements.
- 2) A temporary extended stabilizer to be considered as a backup facility in the case of ACS failure or emergency situations.

5.5.1.1 Permanent Extended Stabilizer

The tether can be used in a permanent manner on Space Station as an aid against aerodynamic drag torques and destabilizing gravity gradient torques.

The capability of achieving a dynamically stable equilibrium is somewhat less important if the Space Station ACS is properly designed to control the instabilities. A dynamically stable configuration, however, would lead to a saving in the power consumption of the CMG's and to a reduction of the requirement on the momentum storage capability.

The real benefit of a permanent tether lies in its ability to reduce the average attitude angles. In the following we limit our discussion to the pitch angle where the effects are more macroscopic.

Three are the possible objectives which one can try to achieve:

- a) keep the excursion of the pitch angle within a set limit.
- b) keep the average of the pitch angle within a set limit.
- c) keep the minimum and maximum of the pitch angle within set limits.

These different objectives are reached for different values of I_d . If we set a 5 degrees limit we find:

- 1) With an $I_d > 20$ the max. excursion of the pitch angle is less than 5 degrees (semi-aperture).
- 2) With an $I_d > 50$ the average value of I_d is less than 5 degrees.
- 3) With an $I_d > 100$ the max. pitch angle is less than 5 degrees and the minimum is more than 0 degrees.

The sizing of the tethered system must be made with the restriction of avoiding a CM shift which would cause an unacceptable level of acceleration within the laboratories. In Fig.5.4-3 the relationship between I_d , d and the acceleration on the laboratories is pictured. For instance if we use an $I_d = 100$, to keep the acceleration within $10 \mu g$, the tether must be attached at 25 m from the CM; if the requirement is $1 \mu g$ a 100 m distance would be required. Such large value of d implies the use of a dedicated boom on which tip to place the Tether Attachment Point. This is scarcely feasible for two reasons:

- a boom so long would imply a degree of structural flexibility which would lessen the effectiveness of the tether stabilizer.
- with a comparatively large value of d (of the same size of the Space Station leading dimension) the attitude dynamics can be negatively affected.

The real solution to this problem is to use a two tether system with the tethers deployed in opposite directions.

The Fig.5.5-1 shows the two possible configurations. In the first one the two tethers are deployed along the local vertical, one upward and the other downward, and their lengths are equal as well as their end masses. It is also possible to shift the position of the stabilizer system along the transverse boom in order to

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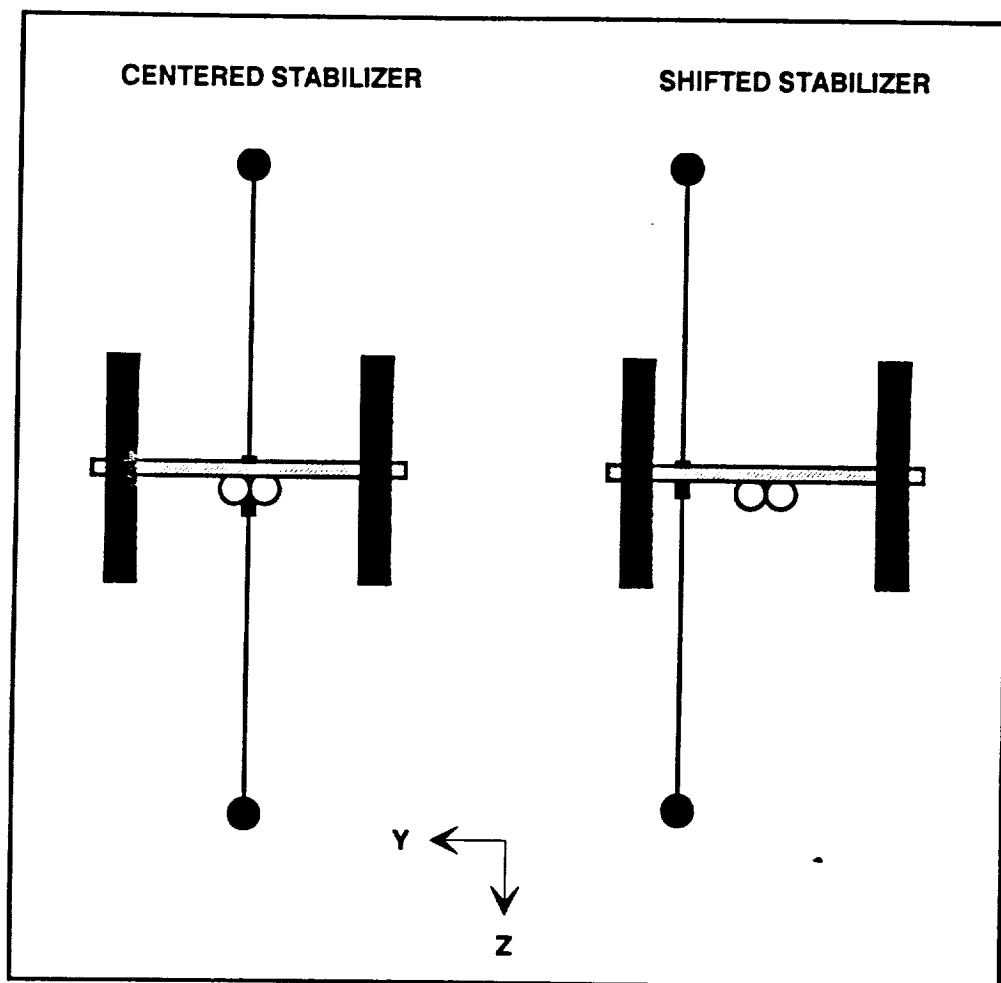


FIG. 5.5-1 PERMANENT EXTENDED STABILIZER CONFIGURATIONS

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reduce the clearance problems. In fact, it can be demonstrated that the system maintains its stabilizing features also if moved far from the CM location.

5.5.1.2 Temporary Extended Stabilizer

In the case of partial or total failure of the primary Attitude Control System several problems could rise in terms of propellant consumption, CMG's saturation, control performance. The worst case being the complete loss of the ability to actively control the attitude of the Station.

In this case, due to the intrinsic instability of the flight mode, the Space Station will tumble of 90 degrees in less than an orbit with large residual librations.

An attractive way to utilize the stabilizing properties of tethers could be the inclusion in the ACS of the Station of an Emergency Stabilizer to be extended only in these contingencies. Figure 5.5-2 depicts the above mentioned concept.

Two observations must be made:

- a) A partial ACS failure would explicate its effect in some orbits given the time scale in which we are operating. Hence there is enough time to perform a tether stabilizer deployment. In the meantime it should be possible to keep the Space Station nearly in the desired attitude using alternate means (RCS if ACS is failed and viceversa).
- b) Given that the situation is an emergency, there is no need to keep low the g level on the laboratories; so a single tether system is sufficient. In this case the TAP should lie approximately on the local vertical through the Space Station center of mass. Notice that a two tether system can be used even in an emergency situation, but the simplicity of operation of the single tether recommends its use.

5.5.1.3 Selected Concept For Preliminary Assessment

In the context of the present study, the task-4 on "Attitude Tether Stabilizer" has been addressed at the

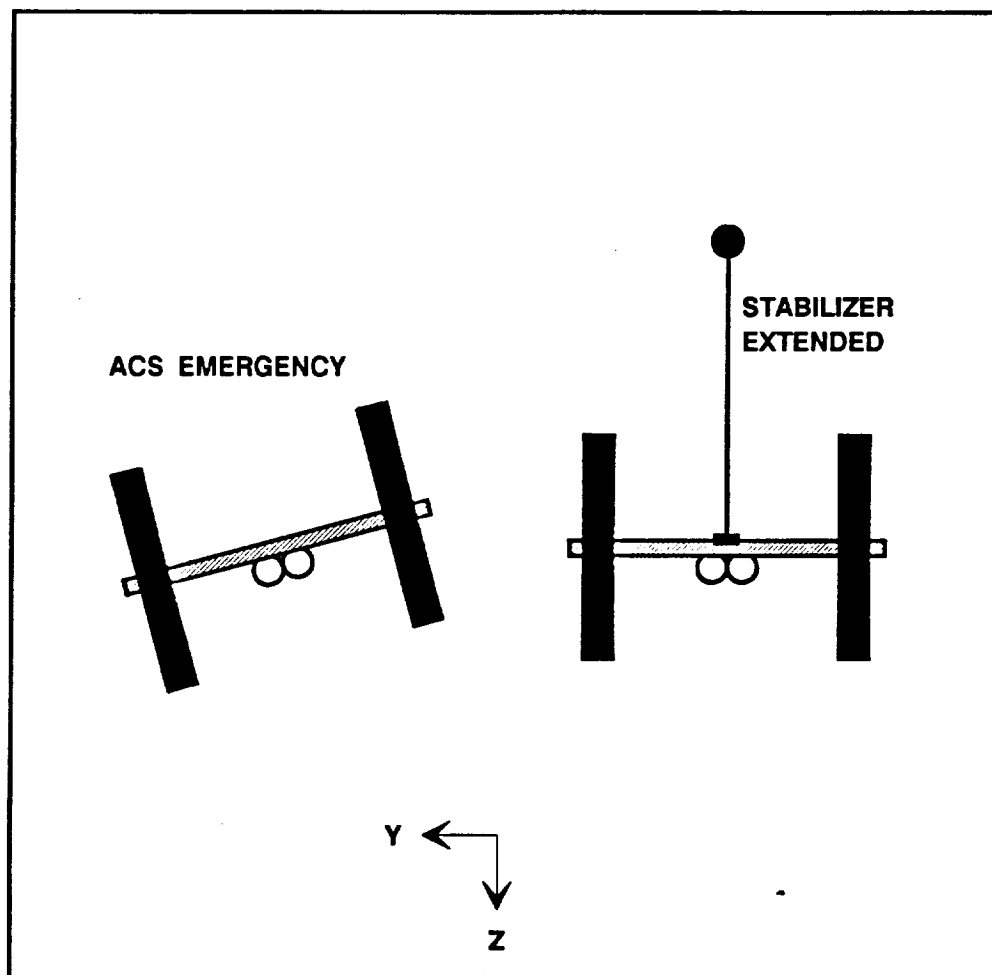


FIG. 5.5-2 TEMPORARY EXTENDED STABILIZER

end of the two years contract. Therefore the relevant analysis effort has been limited in time and extension.

Only one stabilizer concept has been selected for further assessment, specifically the "Emergency Tether Stabilizer". Here we outline the basic motivations of this choice.

Four main issues have been considered:

- 1) Benefit for the attitude control problem.
The permanent stabilizer would allow a saving in the power consumption of the CMG's and the achievement of the LVLH attitude flight mode. The emergency stabilizer would allow the management of ACS emergencies and in turn a benefit for ACS sizing and redundancy design.
- 2) Operational impacts
In presence of a permanent tether system, all the operations that involve proximity maneuvers and rendezvous with the Space Station are complicated by the clearance cone which has to be left for tether motion. For example the Space Station reboosting can excite tether librations in the orbital plane. The emergency stabilizer does not present this problem being normally stowed.
- 3) Disturbances
A permanent tether can be cause of disturbances; in fact thermostructural effects, tether librations and environmental torques on the tether can be a source of disturbance for the Space Station. Again the emergency stabilizer concept implies the absence of extended tethers during normal operations.
- 4) Tether breakage
One big problem of tethered systems is the possibility of tether breakage due to meteorites hit. In the case of tether rupture some kind of problems have to be considered and solved. This can be critical especially for a double tether shifted configuration. The emergency stabilizer concept reduces to a minimum also this kind of problems.

In conclusion, if the benefits offered by both the two stabilizer concepts seem intriguing and valuable to assist the Station ACS, overall considerations on cost minimization and minimum interference with ISS operations dictate that the stabilizer system be as simple as possible and possibly only temporarily extended.

The Emergency Stabilizer concept has been therefore selected for preliminary assessment on the ground of the above considerations.

5.5.2 EMERGENCY TETHER STABILIZER

The selected concept implies the mounting on the central bay of the transverse boom of the Space Station of a relatively simple system constituted by a deployer system, a ballast mass and the tether.

From the operational point of view four operational modes can be envisaged for the stabilizer system:

- 1) Stowed stabilizer
This is the nominal condition for the system that is in a stowed condition during normal activities of the Space Station.
- 2) Stabilizer deployment
In the case of emergency conditions (that are defined in the following), the stabilizer is extended to the appropriate distance from the Station.
- 3) Tether stabilization
In this phase the Space Station is passively stabilized around all the three attitude axes by the tether stabilizer.
- 4) Stabilizer retrieval
At the end of the emergency condition, the stabilizer is retrieved and stowed.

5.5.2.1 Stabilizer Sizing

As seen in paragraph 5.4.2.2, a basic role is played by the product $M_b \cdot d \cdot L$ in the sizing of the stabilizer system. M_b is the extended mass that includes the ballast mass and half the tether mass, d is the distance of the tether attachment point from the Station CM, and L is the tether length.

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The stability window can be described analytically for the inertias ratio of the Space Station in the following way:

$$4(I_y - I_p) > 3M_b d L > -2I_r (K_r + 1) + I_y + K_y (2I_r - I_p) + 2I_r / [K_y (2(K_r - 1) + 1/I_r (I_y + K_y (I_r - I_p)))]$$

As can be seen the lower stability condition is quite complex analytically; utilizing the inertias of the reference Space Station and for $d \ll L$, the stability condition become:

$$10.6 \cdot 10^7 > M_b d L > 7.9 \cdot 10^7$$

It can be demonstrated that for attitude dynamics response considerations, it is preferable to select the $M_b \cdot d \cdot L$ product close to the upper limit. Then, the stabilizer sizing is made assuming:

$$M_b \cdot d \cdot L = 9.8 \cdot 10^7 \text{ Kg} \cdot \text{m}^2$$

The stabilizer has to be mounted on the opposite side of the central bay with respect to the modules cluster, and with the tether aligned with the CM along the Z axis.

Considering the CM position, the bay size and a possible deployer size, the d quantity is approximately 10 m. This value is assumed in order to avoid the design of a boom on which the stabilizer has to be mounted if we want to increase d (unnecessary being 10 m a sufficient arm).

The tether and the ballast mass are sized in order to save total mass and taking into account the impact protection problem.

The following sizing is therefore assumed for the reference stabilizer:

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TETHER TIP DISTANCE FROM STATION CG (M)		
X = 0	Y = 0	Z = -10
BALLAST MASS = 1413 Kg		
TETHER MATERIAL = KEVLAR (1440 Kg/m ³)		
TETHER DIAMETER = 0.008 m		
TETHER LENGTH = 6000 m		
TETHER MASS = 434 Kg		

A preliminary mass of about 650 Kg is assumed for the deployer, leading to the following total mass for the Emergency Stabilizer:

TETHER	434	Kg
BALLAST	1413	Kg
DEPLOYER	650	Kg
STABILIZER MASS	2497	Kg

5.5.2.2 Performance Analysis

The Space Station attitude dynamics has been investigated by SAO in order to assess the performances of the Emergency Tether Stabilizer assuming that no active control (CMG's, RCS) is activated. The numerical results and the relevant analyses are reported in the SAO Final Report (See Section-7).

The conclusions of the previous analytical analysis of stability have been substantially confirmed.

- o The Attitude Tether Stabilizer can passively stabilize the Space Station attitude in a LVLH flight mode.
- o All the three attitude angles (pitch, roll and yaw) are bounded and stable in the case in which the Station reaches reasonable angular displacements with respect to the nominal flight attitude.
- o The effects of external perturbations (orbit eccentricity, air drag, Shuttle docking) are reasonably limited by the Attitude Tether Stabilizer, maintaining the Space Station Attitude dynamics stable and controlled within the required limits.

Nevertheless, many important aspects of the dynamic response of the system have to be deeper analyzed. The present work has been limited in scope and in time, and if the preliminary results seem to be very exciting, the delicate nature of the stabilizing mechanism requires a more thoroughly assessment.

5.5.2.3 Emergency Stabilizer Concept Assessment

In order to assess the ways in which the Emergency Stabilizer could assist the Attitude Control System of the Space Station, we discuss a general functional scheme of the ACS operating modes. In Figure 5.5-3 we have represented the ACS operations in terms of Control System Modes and Flight Modes.

Four basic operating modes are possible for the Attitude Control System:

- o CMG's-only control may be considered as the nominal control mode to maintain the attitude within the

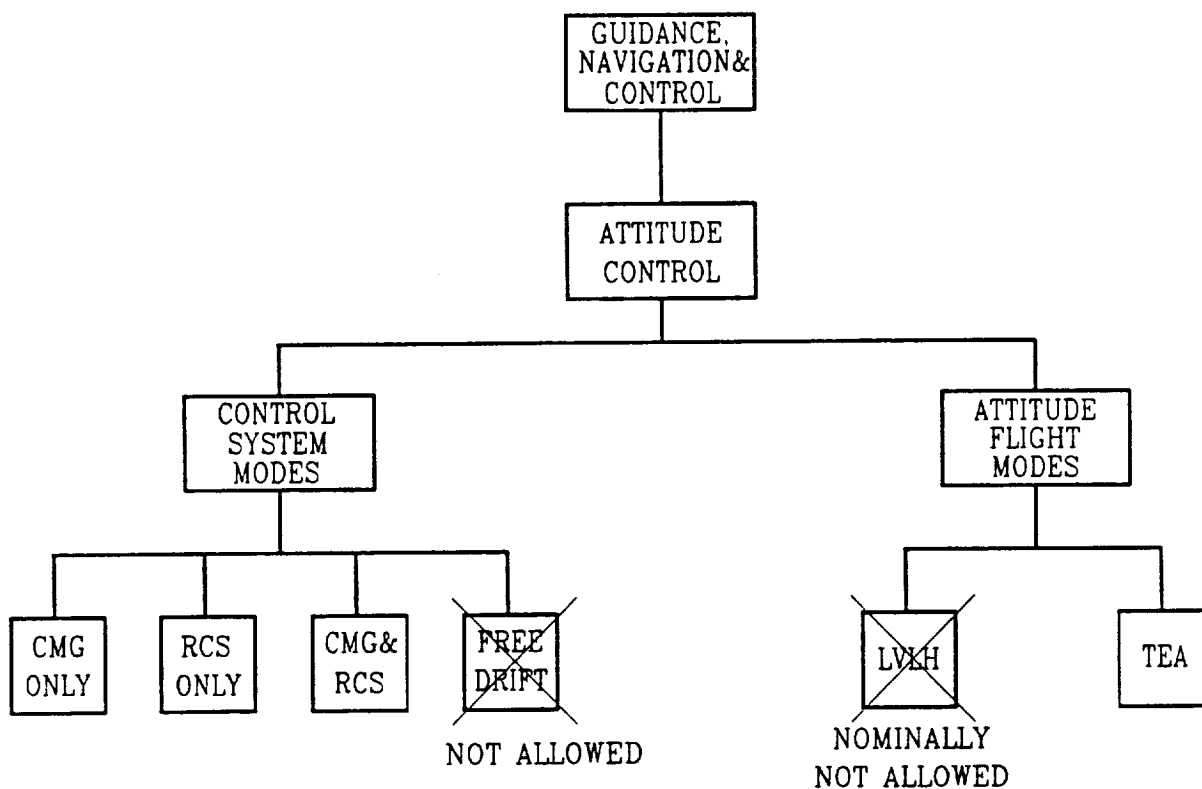


FIG. 5.5-3 ACS CONTROL MODES AND FLIGHT MODES

required limits. CMG's are the primary effectors and the momentum exchange devices during steady-state operations.

- o RCS-only control may be required for orbit maintenance, coarse/transient stabilization, large disturbances control and as backup to the CMG's.
- o Nested CMG-RCS control is operated essentially for CMG's off-load or large attitude errors.
- o For Free Drift mode we mean the situation in which both the CMG's and RCS are inhibited.
For the present Space Station ACS, this flight mode is not allowed due to the high instability of the attitude flight mode.

Two main attitude flight modes are in principle possible:

- o Torque Equilibrium Attitude (TEA) flight mode involves the use of gravity gradient torques to balance the average aerodynamic torque, thus minimizing the CMG's momentum buildup.
- o Local Vertical Local Horizontal (LVLH) flight mode requires the Earth pointing of the Z axis within the $\pm 5^\circ$ limit. This flight mode would lead to a secular momentum buildup well over the 60000 N·M·S each orbit both for CMG's and RCS control modes (see Table-5.4), requiring about 90 Kg of propellant every day. Therefore LVLH attitude cannot be allowed as nominal flight mode, and can be maintained only for short time at the cost of large propellant expenditure.

From the above discussion a first way arises to exploit the Attitude Stabilizer concept : enhance the flexibility of the Space Station ACS allowing for a determined time the "free drift" control mode and the "LVLH" flight mode.

The second way in which the Stabilizer can assist the Space Station ACS is in the management of different emergencies.

As a consequence, four basic situations can be envisaged as possible scenario for the Attitude Stabilizer utilization.

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**MOMENTUM BUILDUP AND PROPELLANT CONSUMPTION
VS. FLIGHT MODE AND ATTITUDE CONTROL MODE**

FLIGHT MODE	TEA		LVLH	
ATTITUDE CONTROL MODE	CMG	RCS	CMG	RCS
SECULAR MOMENTUM (N*M*S/ORBIT)	880	31000	63930	70000
PROPELLANT (KG/DAY)	0.167	22	90	92
PROPELLANT (KG / 90 DAYS- RESUP. PERIOD)	15	1998	8145	8226

TABLE 5.4

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5.5.2.3.1 CMG's Failure

In case of partial or total failure of the CMG's the RCS has to be used as backup attitude control effector. But in this case the propellant consumption increases by order of magnitude.

Table 5.4 shows the momentum buildup and the propellant consumption for TEA and LVLH flight modes and for CMG's and RCS as control effectors. The data are derived from Ref.[7] and the main assumptions used for the RCS are those described in para.5.2.2.

Considering the nominal TEA flight mode (CMG's control) we can see that the total momentum buildup over one orbit is about 900 N·M·S if proper torque equilibrium attitude is maintained. This leads to a small propellant consumption (about 0.2 Kg/Day) for CMG's off-load.

In case of CMG's failure, the RCS is operated to maintain the TEA flight mode. But the thrusters cannot store momentum as the CMG's, and the required total impulse for RCS attitude control is about 31000 N·M·S over one orbit, leading to a propellant consumption of 22 Kg/Day. This figure is essentially due to the pitch control, being the assumed pitch thrusters arm about 3 m. Given the much larger arm, yaw and roll control requires a much lower level of propellant expenditure.

The consumption rate is quite near to the production rate of propellant (22 Kg/day) and considering a 90 days resupply period, about 2000 Kg of propellant are required for attitude control. Since the maximum propellant available, after full resupply (3300 Kg) and orbit reboost (900 Kg), is about 2400 Kg (see para.5.2.2.3), every contingency reboost scenario is no more possible and the scheduled resupply (after 90 days) becomes mandatory.

This is obviously a risky situation that should be carefully evaluated.

Using the Emergency Stabilizer it is possible to reduce the consequences of this kind of failure.

The main problem in this situation is to assure the stability of the Space Station attitude for a long time period, limiting the propellant consumption.

Basically the idea is to use the Attitude Stabilizer to maintain a passively stabilized LVLH flight mode.

RCS thrusters manage the stabilizer deployment and the transition from TEA to LVLH flight modes, and are operated to damp large attitude librations of the Station around the stable flight attitude achieved. In

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this way the propellant consumption is estimated to be very limited, allowing the foreseen contingency reboost scenario.

In addition we have to outline that the Stabilizer total mass (about 2500 Kg) will pay back itself, saving 2000 Kg of propellant if CMG's failure will occur.

5.5.2.3.2 RCS Failure

The failure of the RCS system affects the Attitude Control System operations. In fact, the RCS failure, even if limited in time, could cause the saturation of the CMG's in few orbits, since the momentum cumulated every orbit is of the order of 900 N·M·S (3 axes).

Periodic or continuous momentum management could be performed through the use of gravity gradient and aerodynamic forces, probably without the RCS assistance. This strategy involves the change of the attitude angles w.r.to the TEA condition in order to generate the torques needed to off-load the CMG's.

This is surely possible, but it is required that a complex momentum management logic is incorporated in the Attitude Control System design. Moreover we have to remember that RCS failure impacts on the reboost capability of the Station, hence could be required to feather the solar arrays during a portion of the orbit, assuring the survival electrical power but limiting the Station decay rate.

The management of this situation in which the controls of attitude, power and decay rate are strictly related, would become extremely complex and would probably require the over-sizing of the relevant subsystems.

The utilization of the Emergency Stabilizer allows to simplify the management of this emergency.

After RCS failure, the stabilizer can be extended under CMG's control. The tether length and ballast mass are sized so that, after stabilizer deployment, the Station is in a stable equilibrium attitude.

At this point the CMG's can be inhibited and in case used to damp large attitude librations.

We have to say that the real benefits to employ the Stabilizer in this emergency are of difficult evaluation

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at this time, requiring several in depth analyses. Here, we have just illustrated the possibility of its use.

5.5.2.3.3 Failure at Attitude Control System Level

Here we are considering the situation in which neither the CMG's nor the RCS are able to operate. This is a quite improbable situation (although not impossible, if we think to a failure at the ACS level). In any case it is noticeable that contrarily to most satellites the Space Station is not able to keep its nominal attitude if it is not actively controlled. With the torques acting on the system the Space Station will tumble of 90 degrees in less than one orbit.

This is the more demanding emergency situation where the "free drift" flight mode would be required.

To reach the "free drift" attitude flight mode, the Attitude Stabilizer should be extended, without other effectors assistance, through a fast deployment strategy able also to gradually counteract (during extension) the natural trend of the Station to orientate its transverse boom along the local vertical with extremely high residual librations of the attitude angles.

Again, this is a possibility that has to be investigated in terms of attitude control and deployment strategy, but it seems the only way to reach a "free drift" flight mode for the Space Station attitude.

5.5.2.3.4 Temporary LVLH Attitude Flight Mode

The current payload pointing requirements for the Space Station program would state an attitude stability at ± 5 degree of a LVLH flight mode. The nominal TEA flight mode that implies a large pitch angle, would require the design of mounting adaptors for the payloads that could be adjusted to offset the range of expected TEA orientations.

Nevertheless it is possible to think at particular payloads that would benefit of a LVLH flight mode. Moreover some complex operations could require the reduction of the large pitch angle normally maintained. On the other hand, it can be seen from Table-5.4 the high propellant consumption needed to maintain the LVLH

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orientation even for short time (about 90 Kg for one day).

The flexibility of the Space Station ACS could be increased utilizing the Attitude Stabilizer to achieve the LVLH flight mode for the required time. In fact, the Stabilizer could be extended under ACS control and once the LVLH mode is achieved, limited propellant expenditure would be required, just to damp large attitude librations.

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5.6

MAJOR FINDINGS AND RECOMMENDATIONS

The configuration of the Space Station at the end of the phase-1 of its assembly results in a spacecraft that requires a complex and careful design of the Attitude Control System.

CMG's sizing and RCS propellant allocated depend on the several nominal and emergency operations that have to be managed. In order to not oversize the Attitude Control System, some limitations are imposed to the attitude of the Station, and careful choice should be made of the level of redundancy in the ACS design to limit the probability of functional emergencies.

The stabilizing effect of ballast masses tethered to the Space Station has been investigated as a means to assist the Attitude Control System.

It has been discovered possible to achieve the complete stability around the pitch and roll-yaw axes through a proper design of a tethered system, hence providing a way to passively stabilize the Station attitude.

Two Attitude Stabilizer concepts have been analyzed:

- o A permanent tether Stabilizer designed to alleviate the CMG's requirements.
- o An Emergency Stabilizer to be considered as a backup facility, extended only in the case of emergency situations.

Due to the limited scope of this preliminary study, only one stabilizer concept has been selected for analysis purposes. The "Emergency Tether Stabilizer" has been selected on the basis of considerations on cost minimization and minimum interference with the Station operations, requiring a stabilizer system as simple as possible and possibly only temporarily extended.

The Emergency Stabilizer has been properly sized, leading to a total mass requirement of about 2500 Kg. Then, several simulations have been performed by SAO (see Section-7) confirming the expected stabilizing features.

Four basic situations have been characterized and evaluated in order to assess the Emergency Stabilizer concept both to aid the management of several

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emergencies and to increase the Attitude Control System flexibility.

The attitude tether stabilizer concept seems to have the potential for being an effective way of overcoming some difficulties in the design of the attitude control system of the Space Station. In an "emergency" situation it is able to substitute both the normal attitude actuators (RCS and CMG's). So the Space Station would be able to deal even with major failures of both systems, without the need of complex ACS design in terms of sizing and redundancy. Moreover it is able to enhance the ACS flexibility allowing a "free drift" control and the "LVLH" flight mode.

The total stabilizer mass is relatively low and it seems possible to keep to a minimum undesired side effects and impacts on the Station configuration.

At this time, the real benefits of the inclusion of the Attitude Stabilizer in the ACS design are of difficult evaluation. In fact, beyond the purpose of the present work, several in depth analyses have to be performed and a detailed knowledge of the present ACS design should be available. In spite of that the Attitude Tether Stabilizer represents one of the more intriguing ways in which "Tethers" can enhance the Space Station capabilities.

Recommendations

- o It is highly recommended that the Stabilizer concept is considered and evaluated by people in charge of the design of the Space Station Attitude Control System.
- o Non linearities, several kind of disturbances and in general the delicate nature of the tether stabilizing effect should be deeper analyzed.
- o More refined computer simulations should be performed with the aim to investigate the attitude dynamics of the tether-stabilized Station and to devise proper control strategies to extend the Stabilizer.
- o The benefits of the inclusion in the ACS design of the Emergency Stabilizer should be assessed in terms of performances, mass, propellant, CMG's sizing, redundancy philosophy and contingency reboost scenario.

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- o Finally, it is recommended that, after the Shuttle mission in which will be deployed for the first time the "Tethered Satellite System" (TSS-1 mission, presently scheduled in 1991), the available data on Orbiter attitude during tethered operations are analyzed in order to understand the real stabilizing properties of tethers.

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SECTION-6 APPENDICES

6.1 REFERENCES

- [1] Space Station Baseline Phased Program - Characterization Notebook (preliminary) - August 1987.
- [2] Kroll, K.R., "Tether Implications on Space Station Gravity Level", International Conference on Tethers in Space, Arlington (VA), September 1986.
- [3] Sharpe, A. (Ed.), "Low Acceleration Characterization of Space Station Environment", Teledyne Brown Engineering, Final Report for NASA-MSFC, Contract NAS8-36122, October 1985.
- [4] Cour-Palais, B.G., "Meteoroid Environment Model - 1969 (Near Earth to Lunar Surface)", NASA SP-8013, March 1969.
- [5] Kessler, D.J., "Orbital Debris Environment for Space Station", SSC-20001, 1986.
- [6] "CARINA Micro-g Utilisation Aspects", AERITALIA Report, CR-RP-AI-004, December 1988.
- [7] L. De Ryder, P. Troutman, M. Heck, "The impact of asymmetric physical properties on large space structures", AIAA SDM issues of the International Space Station, Williamsburg, Virginia, April 1988, Paper No. 88-2486.
- [8] Tethered Gravity Laboratories Study - Quarterly Progress Report # 1 for NASA-JSC, Contract NAS9-17877, AERITALIA Report, TG-MR-AI-001, June 1988.
- [9] Tethered Gravity Laboratories Study - Quarterly Progress Report # 2 for NASA-JSC, Contract NAS9-17877, AERITALIA Report, TG-MR-AI-002, September 1988.
- [10] Tethered Gravity Laboratories Study - Quarterly Progress Report # 3 for NASA-JSC, Contract NAS9-17877, AERITALIA Report, TG-MR-AI-003, December 1988.
- [11] Tethered Gravity Laboratories Study - Quarterly Progress Report # 4 for NASA-JSC, Contract NAS9-17877, AERITALIA Report, TG-MR-AI-004, March 1989.

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- [12] Tethered Gravity Laboratories Study - Quarterly Progress Report # 5 for NASA-JSC, Contract NAS9-17877, AERITALIA Report, TG-MR-AI-005, June 1989.
- [13] Tethered Gravity Laboratories Study - Quarterly Progress Report # 6 for NASA-JSC, Contract NAS9-17877, AERITALIA Report, TG-MR-AI-006, September 1989.
- [14] Tethered Gravity Laboratories Study - Quarterly Progress Report # 7 for NASA-JSC, Contract NAS9-17877, AERITALIA Report, TG-MR-AI-007, December 1989.
- [15] "Low Gravity Processes Identification", Tethered Gravity Laboratories Study - Task-2 Final Report for NASA-JSC, Contract NAS9-17877, AERITALIA Report, TG-RP-AI-001, February 1989.
- [16] "Active Center of Gravity Control", Tethered Gravity Laboratories Study - Task-1 Final Report for NASA-JSC, Contract NAS9-17877, AERITALIA Report, TG-RP-AI-021, November 1989.

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6.2 ACRONYMS

ACS	Attitude Control System
ADCS	Attitude Determination and Control System
BCU	Battery Control Unit
BRU	Battery Regulation Unit
CG	Center of Gravity
CM	Center of Mass
CMG	Control Moment Gyro
CTU	Central Terminal Unit
DBU	Digital Bus Unit
DC	Direct Current
EPDS	Electrical Power and Distribution System
FOV	Field Of View
GDM	Guide Drive Mechanism
ISS	International Space Station
LVLH	Local Vertical Local Horizontal
MFA	Multi Furnace Assembly
MLI	Multi Layer Insulation
MMU	Mass Memory Unit
OBDAH	On Board Data Handling
PCDU	Power Control and Distribution Unit
P/L	Payload
PM	Payload Module
RCS	Reaction Control System
RF	Radio Frequency
RFDU	Radio Frequency Distribution Unit
RMS	Remote Manipulator System
RTG	Radioisotope Thermal Generator
RTU	Remote Terminal Unit
SAO	Smithsonian Astrophysical Observatory
SM	Service Module
SMU	Software Memory Unit
STS	Space Transportation System
TAP	Tether Attachment Point
TBD	To Be Determined
TBV	To Be Verified
TCS	Thermal Control System
TDE	Thruster Drive Electronics
TDM	Translation Drive Mechanism
TEA	Torque Equilibrium Attitude
TSS	Tethered Satellite System
TT&C	Telemetry and Telecommand
VCHP	Variable Conductance Heat Pipes
VGL	Variable Gravity Laboratory
WDE	Wheel Drive Electronics

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SECTION - 7

SMITHSONIAN ASTROPHYSICAL OBSERVATORY FINAL REPORT

**ANALYTICAL INVESTIGATION OF
TETHERED GRAVITY LABORATORY**

Aeritalia Contract 8864153

FINAL REPORT

For the period 25 January 1988 through 24 January 1990

Principal Investigator

Dr. Enrico C. Lorenzini

Co-Investigators

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February 1990

Prepared for
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Summary

This Final Report deals with the three topics of investigation summarized hereunder:

1) Active Center of Gravity Control

The dynamic response and the apparent acceleration level on board the station are evaluated for three tethered system acted upon by environmental and gravitational perturbations. The effects of longitudinal dampers on the acceleration levels are demonstrated through numerical simulation. The performance of each tethered system is evaluated based on the acceleration levels induced on the Space Station.

Furthermore, the capability of a tethered system in damping the first flexural mode of the single-transverse-boom Space Station is analyzed.

2) Variable Gravity Laboratory

The analysis of the dynamic response of the elevator during transfer maneuvers is carried out by means of numerical simulations. An effective algorithm for the elevator's crawling along the tether has been devised.

The acceleration levels on board the elevator are computed for crawling maneuvers and station keeping phases. Damping algorithms for controlling the lateral/librational and longitudinal oscillations are devised in order to reduce the acceleration noise on board the elevator. The attitude dynamics of the elevator during crawling maneuvers is also analyzed.

3) Tether Stabilizer for Space Station Attitude

A tether system to stabilize the Space Station in case of malfunctioning or failure of the attitude control devices is analysed. The design parameters are derived based on considerations of system stability. The impact of such tether system on the Space Station attitude motion is evaluated through numerical simulations.

Figure Captions

- Figure 2.1 Reference frames and coordinates.
- Figure 2.2 Schematic of Double Tether Centered System (DTCS) and its discretization model.
- Figures 2.3(a)-(d) Dynamic response of Double Tether Centered System (DTCS). Orbital parameters: 28.5° inclination, 180° initial anomaly, initially circular orbit, Sun at the Summer Solstice. Environmental and gravitational perturbations: thermal fluxes in and out of tethers, dynamic atmospheric density model (Jacchia's 1977), J_2 -gravity-term. Initial tether temperature equal to 380°K . Two tether longitudinal dampers are activated. In (d) the two longitudinal dampers are deactivated.
- Figure 2.4 Schematic of Single Tether System (STES) and its discretization model.
- Figures 2.5(a)-(b) Dynamic response of STES. The assumptions are like in Figs. 2.3. One longitudinal damper, tuned to the bobbing frequency of the tether, is activated.
- Figure 2.6 Schematic of Double Tether System with Space Elevator (DTSSE) and its discretization model.
- Figure 2.7 Schematic of the 2-DOF system which models the bobbing oscillations of the lower tether. The station is modelled by the wall, m_1 is the elevator and m_2 is the lower-end-platform.
- Figures 2.8(a)-(e) Dynamic response of the DTSSE. The assumptions are like in Figs. 2.3. Three

longitudinal dampers, each one tuned to the bobbing frequency of the associated tether, are activated.

- Figure 2.9(a)-(b) (a) Schematic of Tethered Dynamic Absorber for abating the first flexural mode of the single-transverse-boom station; (b) Schematic of the equivalent system of Tethered Dynamic Absorber.
- Figure 2.10(a)-(b) (a) Effective static moment required of a Tethered Dynamic Absorber for avoiding tether slackness vs modal frequency. The flexural modal amplitude is assumed equal to 0.1 m; (b) Masses of end-platform, tether, and total mass of Tethered Dynamic Absorber vs tether length for both steel and kevlar tether materials. The effective static moment is 10^8 kg-m and the frequency of the first flexural mode is 0.1 Hz.
- Figure 3.1 Schematic of the variable gravity laboratory (VGL).
- Figures 3.2(a)-(e) Parametric analysis of the Mirror Image Motion Control (MIMCL) for a crawling maneuver from 141 m to 154 m off the station.
- Figures 3.3(a)-(e) Parametric analysis of the MIMCL for a crawling from 2667 m to 10242 m off the station.
- Figures 3.4(a)-(e) Dynamic response of VGL for a transfer maneuver from 141 m to 154 m off the station.
- Figures 3.5(a)-(c) Characteristics of "string-like" lateral vibrations of the VGL.
- Figures 3.6(a)-(g) Dynamic response of VGL for a transfer maneuver from 1404 m to 2667 m off the station.
- Figures 3.7(a)-(g) Dynamic response of VGL for a transfer maneuver from 2667 m to 10242 m off the station.

- Figures 3.8(a)-(g) Dynamic response of VGL for a transfer maneuver from 2667 m to 10242 m off the station with in-plane libration and lateral dampers activated.
- Figures 3.9(a)-(e) Dynamic response of the VGL for fast crawling maneuvers (FCM) from 1404 m to 2667 m off the Station with in-plane libration and lateral dampers activated ($K_\theta = K_\epsilon = 1$).
- Figures 3.10(a)-(d) Spectra of the acceleration components (front and longitudinal) for a station-keeping phase ($l_2 = 2667$ m) with and without the action of the libration/lateral dampers.
- Figures 3.11(a)-(c) Magnitude of Frequency Response Function (FRF) at the elevator for longitudinal perturbations originated at the tether/station attachment point. No tether material damping. No longitudinal dampers.
- Figures 3.12(a)-(c) Magnitude of Frequency Response Function (FRF) at the elevator for longitudinal perturbations originated at the tether/station attachment point. 2% viscous tether material damping for first longitudinal mode. No longitudinal dampers.
- Figure 3.13 Schematic of VGL with attitude reference frames.
- Figure 3.14 System oscillatory modes vs distance between VGL and Space Station.
- Figures 3.15(a)-(g) Dynamic response of the VGL for a Station-keeping at 2667 m off the station with attitude dynamics
- Figures 3.16(a)-(f) Spectra of the accelerations acting upon two points within VGL for a station keeping at 2667 m off the Station

- Figures 3.17(a)-(f) Dynamic response of the VGL for a crawling maneuver from 2667m to 10242 m off the Station with attitude dynamics.
- Figures 3.18(a)-(f) Dynamic response of the VGL for a crawling maneuver from 2667 m to 10242 m off the station with in-plane libration/lateral dampers activated and attitude dynamics.
- Figure 4.1 Schematic of SS with Tether Stabilizer.
- Figures 4.2(a)-(i) Attitude dynamic response of the Station acted upon by tether, gravity gradient, and aerodynamic torques. The principal axes of inertia are rotated by a pitch angle of -6.27° with respect to the geometric body frame of the Station.
- Figure 4.3 Attitude dynamic response of the Station acted upon by tether, gravity gradient, and aerodynamic torques for 10° initial values of the three attitude angles.

1.0 INTRODUCTION

This is the Final Report on "Analytical Investigation of Tethered Gravity Laboratory" prepared by the Smithsonian Astrophysical Observatory (SAO) under contract 8864153 for Aeritalia, Societa' Aerospaziale Italiana. This report covers the period from 25 January 1988 through 24 January 1990. The Principal Investigator for this contract is Dr. Enrico C. Lorenzini and the Co-Investigators are Dr. Mario Cosmo and Mr. David A. Arnold.

2.0 ACTIVE CENTER OF GRAVITY CONTROL

2.1 Introductory Remarks

The analysis performed by Aeritalia (AIT) has identified four different configurations of tethered systems to be attached to the initial IOC (transverse boom only) configuration of the space station (SS). These four tethered systems were designed not only to provide alternative ways of controlling the acceleration levels on board the SS but also for providing additional capabilities such as a variable gravity laboratory and damping of flexural modes of the station.

The control of the static position of the center of gravity of the overall system and hence of the acceleration bias on board the SS has been carried out by Aeritalia. The results of the analysis, shown in the AIT Quarterly Progress Report 1, have been used by Aeritalia to design four different tethered configurations as follows:

1. Double Tether Centered System (DTCS)
2. Single Tether System (STS)
3. Double Tether System with Space Elevator (DTSSE)
4. Shifted Double Tether System (SDTS)

In particular system 4 had been designed to control the attitude of the station (directly related to the acceleration levels) but was later discarded by Aeritalia based on considerations of operational constraints.

Before selecting the best configuration for controlling the apparent gravity on board the SS, a fundamental topic must be addressed, namely the evaluation of the acceleration noise produced on board the station by each one of the three tether configurations.

On one hand a tethered system attached to the space station provides some unique capabilities for the station as briefly mentioned in the previous section. On the other hand since a tethered system has a large exposed area and covers long distances it is affected by several environmental perturbations such as aerodynamic drag, thermal disturbances, and non-spherical gravity effects of which the J_2 term is the most important. The effects of these perturbations are small but non-negligible when we consider acceleration levels as low as 10^{-6} g.

For this reason each one of the three tethered configurations, which passed the first selection by Aeritalia, were further investigated by SAO to assess the acceleration noise level transmitted to the space station when each tethered system is acted upon by environmental perturbations.

Based upon previous experience with tethered systems for microgravity applications, we know that longitudinal (along the tethers) dampers are necessary for achieving a microgravity level well below 10^{-5} g. The thermal perturbations, in fact, cause quasi-impulsive variations of the tether lengths each time the system crosses the terminator. Consequently the longitudinal component of the acceleration on board the SS builds up over several orbits exceeding the 10^{-5} g level, unless longitudinal dampers are added to the system.

2.2 Simulation Model

The analysis of the dynamics of the three tethered systems attached to the space station has been carried out by means of one of the SAO computer code, developed under a different contract. The code models a tethered system with a number of massive, point-like lumps connected by springs and dashpots. The lumps are either tether lumps or platform lumps and their masses are consequently very different. A numerical integrator, which can be a variable-step 4th-order Runge-Kutta or a predictor-corrector, integrates the acceleration components of each lump with respect to a rotating orbiting frame ORF (see Fig. 2.1). ORF rotates on a circular orbit at the constant orbital rate Ω for that altitude. The origin of ORF is selected by the user at the beginning of the simulation run. Usually it is chosen to coincide with the system center of mass (CM) or the system orbital center (CO) or the space station itself. As the simulation progresses the origin of ORF and the tethered system depart from one another owing to the environmental and orbital perturbations.

The cartesian coordinates of the lumps are the integration variables of the computer code. Another set of variables is also used to provide a more pictorial and to some extent physical description of the system dynamic. This set of coordinates is formed by (see Fig. 2.1): the distances l_i between successive lumps, the deflections ϵ 's of the inner lumps with respect to the line through the end-platforms, and the in-plane and out-of-plane libration angles of the overall system with respect to the local vertical (LV). The deflections ϵ 's are then projected onto the in-plane components ϵ_i 's and the out-of-plane components ϵ_o 's. This new set of variables will be used extensively in the next sections.

The simulation code is also equipped with subroutines which model aerodynamic forces, gravity forces, and thermal fluxes.

Because of the very low acceleration levels in which we are interested, an accurate model of external forces is necessary in order

to simulate with high enough fidelity the effects of the environment on the system dynamics. The main external perturbations are: the gravitational forces F_g , the aerodynamic forces F_d , and the thermal effects on the tensional forces F_T . The gravity model of the computer code is not linearized and takes into account the first zonal harmonic of the gravity field (J_2 -term). The J_2 -term has a secular effect on such orbital parameters of the system as mean anomaly, argument of perigee, and right ascension of the ascending node. The J_2 -term also affects the librations and lateral oscillations (see next sections) of long tethered systems like those under analysis.

The drag model is an analytical fit of Jacchia's 1977 density model. The atmospheric density varies as a function of the altitude (the Earth's oblateness is also considered) and the local exospheric temperature. The latter takes into account the diurnal variation, which is a function of the argument of longitude and solar activity.

The thermal inputs on the tether segments are: the solar illumination, the Earth's albedo, and the IR Earth radiation. The only cooling process is the emitted radiation. The position of the terminator is computed as a function of the Sun's position along the ecliptic. As the system crosses the terminator, the tether temperature varies abruptly; consequently the tether segments expand or contract and the tethers' tensions exhibit steep variations. The $N-1$ equations of the thermal balance of the tether segments are added to the equations of motion and integrated numerically by the integrator.

2.3 Noise Abatement Through Longitudinal Dampers

The longitudinal tether oscillations triggered by the thermal shocks can be abated by adding a longitudinal damper to each tether segment. The damper can be a passive device in the form of a spring-dashpot system placed in series to the tether, or it can be active. In the latter case each reel controls the associated tether according to a proportional-derivative control law. Since the tethers of the DTCS are relatively stiff and consequently the elastic stretches are only a few centimeters long, passive dampers can be easily implemented by

inserting spring-dashpot devices between the tethers' tips and the attachment points to the end-platforms.

In reference [1] an optimization of the dynamic response of a longitudinal damper in series with a tether has been carried out. The damper-plus-tether system is a third order oscillating system if the intrinsic mass of the damper is neglected. The damper parameters, ω_d = angular frequency and b_d = damping coefficient, which provide the fastest decay time after the action of an impulsive perturbation, have been computed in reference [1]. The results indicate that a damper tuned to the tether bobbing frequency is a sub-optimal solution. The decay time may actually be faster for a detuned damper at the expenses, however, of a larger elastic tether stretch and hence a larger fluctuation of the acceleration. We have therefore opted for the sub-optimal tuned damper. Reference [1] also indicates the best value of damping coefficient for a tuned damper. The optimal value of b_d is consistent with a damping ratio equal to 0.9 for the response of the hypothetical 1-DOF damper system (the damper is assumed to be directly connected to the end-platform in this hypothetical system). The value of b_d is therefore given by:

$$b_d = 1.8 EA/(l\omega_0) \quad (1)$$

where ω_0 is the bobbing frequency of the tether which is also equal to the damper frequency ω_d since the damper is tuned, and l is the length of tether segment.

2.4 Acceleration Noise for Different Configurations

2.4.1 Double Tether Centered System

In order to simulate the dynamic response, the Double Tether Centered System (DTCS) proposed by Aeritalia has been modelled by 9 lumps: 3 lumps for the platforms and 3 lumps for each one of the tethers as shown in Fig. 2.2. The design parameters of the DTCS, with the orbital center at the space station, are therefore as follows (see Fig. 2.2):

$$M_1 = 3050 \text{ kg}$$

$$M_2 \text{ (SS)} = 200 \times 10^3 \text{ kg}$$

$$M_3 = 5400 \text{ kg}$$

$$l_1 = 8360 \text{ m, } m_{T1} = 2490 \text{ kg, } \text{dia}_1 = 0.012 \text{ m}$$

$$l_2 = 6000 \text{ m, } m_{T2} = 1191 \text{ kg, } \text{dia}_2 = 0.010 \text{ m}$$

where m_{T1} and m_{T2} are the masses of the lower and upper tether respectively. If we adopt aluminum tethers, as proposed by Aeritalia, the stiffness coefficients of the two tethers are $EA_1 = 8,482,300 \text{ N}$ and $EA_2 = 5,890,486 \text{ N}$ respectively. We also adopt a viscous damping model for the longitudinal oscillations of the tethers. This implies that the ratio between the axial tether viscosity EA' and its stiffness EA is constant; consequently the critical viscosity is a linear function of the longitudinal wavelength. This damping model is not agreed upon by all investigators. Nevertheless, it is a conservative model and is therefore a prudent choice before any other experimentally tested damping model of tether material is produced. For the simulation runs, shown later on, we assume a critical wavelength for longitudinal waves of about 60 m. This means that any longitudinal wave, propagating along the tether, with a wavelength shorter or equal to 60 m is asymptotically damped. The values of axial tether viscosities for the DTCS, consistent with the above critical wavelength, are $EA_1' = 30,000 \text{ N-sec}$ and $EA_2' = 20,000 \text{ N}$ for the lower and upper tether respectively. The orbital altitude of the system is 352 km, the inclination is 28.5° , and the initial orbital anomaly is equal to π for the three configurations under analysis.

For the first simulation run of the DTCS we assume that the system has no longitudinal dampers. The simulation starts with the system aligned with the local vertical. The initial conditions are equilibrium initial conditions which means that the initial elastic stretches have been appropriately computed to balance the external forces. The Sun is at the Summer Solstice and the initial tether

temperature T is the equilibrium temperature of an aluminum tether which is steadily exposed to Sun rays perpendicular to its longitudinal axis. The thermal characteristic of the aluminum tether are summarized below:

$$c = \text{specific heat} = 962 \text{ J/Kg-}^{\circ}\text{K}$$

$$\rho = \text{volume density} = 2700 \text{ kg/m}^3$$

$$\epsilon = \text{emissivity} = -0.01 + 6.6 \times 10^{-7} T^2$$

$$\alpha = \text{absorptivity} = 0.2$$

$$\alpha_{\text{IR}} = \text{IR absorptivity} = 0.05$$

$$\delta = \text{coefficient of thermal expansion} = 1.3 \times 10^{-5} \text{ }^{\circ}\text{K}^{-1}$$

The drag model, described briefly in Section 2.3, has an average exospheric temperature of $900 \text{ }^{\circ}\text{K}$ (the local exospheric temperature in the model depends on the argument of longitude). The duration of the simulation run is 8000 sec or 1.5 orbits since the orbital period is equal to 5495 sec.

Two longitudinal dampers are placed in series to the two tether segments. The characteristics of the dampers are as follows:

$$\omega_{d1} = \omega_{01} = 0.4927 \text{ rad/s} \quad (\text{lower tether})$$

$$b_{d1} = 3,707 \text{ N/(m/s)}$$

$$\omega_{d2} = \omega_{02} = 0.4113 \text{ rad/s} \quad (\text{upper tether})$$

$$b_{d2} = 4,297 \text{ N/(m/s)}$$

The relevant features of this simulation run are shown in Figures 2.3(a)-(c). Specifically Figure 2.3(a) shows the atmospheric density profile at the SS over 1.5 orbits according to the model implemented in our simulation code. The density profile is valid for all the simulation runs shown in this report. Figure 2.3(b) depicts the temperatures of the lower and upper tether respectively. The two

temperature profiles are slightly different from one another owing to the different tether diameters. Since the lower tether is thicker and more massive its thermal inertia is larger than the upper tether. From the temperature profiles it is easy to see the effect of the changing view factor and the eclipse. In particular the derivative of the temperature is discontinuous at each crossing of the terminator.

The effect of all the environmental perturbations is clearly shown in Figure 2.3(c) which depicts the longitudinal, front and side components of the acceleration measured on board the SS. These components are referred to the tether-body reference frame which provides an accurate representation of the SS body-reference-frame (our model does not have the rotational dynamics of the platforms) since it is reasonable to assume that, for small angles, the SS librates like the overall system. The front component is generated by the air drag acting upon the SS (cross section $A = 1400 \text{ m}^2$), the end platforms ($A = 10 \text{ m}^2$ for each platform), the lower tether ($A = 100.3 \text{ m}^2$), and the upper tether ($A = 60 \text{ m}^2$). The side acceleration component is negligible. The longitudinal component is affected primarily by the thermal shocks. The shocks force the system to ring, in particular they excite the longitudinal tether oscillations which, in the absence of longitudinal dampers, are only moderately abated by the tether material damping.

Finally, Fig. 2.3(d) depicts the acceleration components of the acceleration for the same system with disactivated longitudinal dampers. The effects of the longitudinal dampers are evident: (1) the acceleration fluctuations are rapidly reduced to zero after the terminator's crossings; and (2) the values of the peaks of the longitudinal component are strongly reduced.

2.4.2 Single Tether System

The second configuration proposed by Aeritalia is a Single Tether System (STES) designed to compensate for the static position of the system orbital center. We have simulated the dynamic of this system in order to evaluate its acceleration noise. Following a path similar to

that of the previous section we model the system as follows: two lumps for the platforms and two for the tether. Since this system is quite stiff a higher number of lumps would result in very long CPU times, while 4-lumps provide enough resolution for the purpose of our analysis. The design parameters of STES, proposed by Aeritalia, are shown below (see Fig. 2.4):

$$M_1 = 70.4 \text{ kg}$$

$$M_2(\text{SS}) = 200 \times 10^3 \text{ kg}$$

$$l_1 = 1660 \text{ m}, \quad m_T = 79 \text{ kg}, \quad \text{dia} = 0.005 \text{ m}$$

which result in a tether stiffness coefficient $EA = 1,472,622 \text{ N}$ and an axial tether viscosity $EA' = 5000 \text{ N-sec}$ if we assume tether material characteristics like those of the DTCS. The tether material is, as suggested by Aeritalia, aluminum with the thermal properties given by equations (1) of Section 2.4.1.

A simulation of STES has been run according to the same assumptions described in Section 2.4.1. Specifically one longitudinal damper with the following characteristics

$$\omega_d = \omega_{01} = 2.842 \text{ rad/sec}$$

$$b_d = 562 \text{ N/(m/s)}$$

is placed in series to the tether. It is worth mentioning that since our simulation code models the platforms as point masses the simulation model does not reflect the offset between the space station's CM and the geometrical center of the microgravity laboratory on board the station. In other words when the simulation code computes the acceleration level on board the station it views the station as a point.

Figure 2.5(a) shows the components of the acceleration measured on board the SS. The front component, which is primarily related to the air drag acting upon the SS frontal section, is the largest component. The side component is negligible. The longitudinal component is also relatively smooth [see also the enlargement in

Figure 2.5(b)). This is most probably due to the shorter tether length, with respect to the DTCS, and also to the lighter end-platform. A lighter end-platform allows the tether to shorten or lengthen more freely following a temperature variation, without causing a large fluctuation of the tension, and hence of the apparent acceleration.

The longitudinal acceleration component, as explained before, is not computed at the location of the microgravity laboratory. Actually, the bias of the longitudinal acceleration corresponds to a 1-m-offset between the station CM and the microgravity lab. Consequently the bias at the microgravity lab is close to zero. In conclusion the STES appears to be less noisy than the DTCS. Both for STES and DTCS the acceleration levels are well within the 10^{-5} g microgravity requirement on board the station. In particular the tether-related acceleration fluctuations around the dc value on board the SS are of the order of 10^{-8} g for STES.

2.4.3 Double Tether System with Space Elevator

The third configuration proposed by Aeritalia is a Double Tether System with Space Elevator (DTSSE). Like for the first configuration we adopt the rounded-off design parameters, indicated by Aeritalia, for the upper side of the system (where the elevator is located) and we compute the tether length of the lower side in order to have the orbital center at the SS. With reference to Figure 2.6 the design parameters of the DTSSE are

$$M_1 = 2250 \text{ kg}$$

$$M_2 \text{ (EL)} = 2250 \text{ kg}$$

$$M_3 \text{ (SS)} = 200 \times 10^3 \text{ kg}$$

$$M_4 = 3460 \text{ kg}$$

$$l_1 = 4060 \text{ m, } m_{T1} = 774 \text{ kg, } \text{dia}_1 = 9 \text{ mm}$$

$$l_2 = 1640 \text{ m, } m_{T2} = 313 \text{ kg, } \text{dia}_2 = 9 \text{ mm}$$

$$l_3 = 4977 \text{ m}, m_{T3} = 949 \text{ kg}, \text{dia}_3 = 9 \text{ mm}$$

The three tether segments have therefore the same stiffness coefficient $EA = 4,771,294 \text{ N}$ and the same axial viscosity $EA' = 16,500 \text{ N-sec}$ consistent with the values adopted in the previous sections. The tethers are made of aluminum as proposed by Aeritalia. The discretization model for the DTSSE is a 10-lump-model: 2 evenly spaced lumps for each of the three tether segments and 4 lumps for the 4 platforms.

A simulation of the DTSSE has been run according to the same assumptions described in Section 2.4.1 with the exception of the initial temperature which has been reduced from 380°K to 335°K in order to be closer to the equilibrium value. In particular, three longitudinal dampers have been added to the system: one for each tether segment. This time, however, it is more complex to compute the bobbing frequencies of the two tether segments above and below the elevator because these two longitudinal DOF's are coupled. Since the station is two orders of magnitude heavier than the other platforms we can reasonably assume that the vibrations of the lower tether are decoupled from the vibrations of the upper tether. The bobbing frequency of the upper tether can be computed, therefore, by assuming that the upper tether is a 1-DOF system. The bobbing frequency of the upper tether is

$$\omega_{03} = \sqrt{EA/(l_3 m_{Q3})} \quad (2)$$

where the equivalent mass $m_{Q3} = (M_3 + 1/2 m_{T3})M_2/(M_3 + M_2 + 1/2 m_{T3})$ for the mass of the upper tether. The lower tether subsystem (elevator plus end-mass plus two tether segments) can be modelled, with respect to the bobbing oscillations, as a 2-DOF system. Such a system is schematically depicted in Figure 2.7. The mass m_1 is the elevator and m_2 the end-platform. The stiffness of the two tethers are $k_1 = EA/l_1$ and $k_2 = EA/l_2$, respectively. The eigenfrequencies and eigenvector of this relatively simple system can be found in any book

about multi-DOF-system dynamics. Specifically the eigenfrequencies are given by:

$$\omega_{0i}^2 = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad i = 1, 2 \quad (3)$$

where

$$\begin{aligned} a &= m_1 m_2 \\ b &= -[m_1 k_2 + m_2 (k_1 + k_2)] \\ c &= k_1 k_2 \end{aligned} \quad (4)$$

After solving equation (3) for our system we obtain

$$\begin{aligned} \omega_{01} &= 0.5395 \text{ rad/s} \\ \omega_{02} &= 1.3611 \text{ rad/s} \end{aligned} \quad (5)$$

The amplitude ratios between the two components A_i (first DOF) and B_i (second DOF) of the eigenvectors associated with the eigenfrequencies ω_{0i} are given by

$$\begin{aligned} r_1 &= \frac{A_1}{B_1} = \frac{k_2 - \omega_{01}^2 m_2}{k_2} \\ r_2 &= \frac{A_2}{B_2} = \frac{k_2 - \omega_{02}^2 m_2}{k_2} \end{aligned} \quad (6)$$

After substituting the numerical values of our system we obtain

$$\begin{aligned} r_1 &= 0.3475 \\ r_2 &= -3.1549 \end{aligned} \quad (7)$$

This result implies that the natural longitudinal oscillations of the 1st DOF (the tether segment between EL and SS) are dominated by the second eigenfrequency ω_{02} . On the other hand, the natural longitudinal oscillations of the 2nd DOF (the tether segment between EL and the end-platform) are dominated by the first eigenfrequency

ω_{o1} . In order to dissipate the energy of longitudinal oscillations it is therefore convenient to tune the damper between EL and SS to ω_{o2} and the damper between EL and the end-platform to ω_{o1} . The characteristics of the three dampers are finally as follows:

$$\begin{aligned}
 \omega_{d1} &= 0.5395 \text{ rad/s} \\
 \omega_{d2} &= 1.3611 \text{ rad/s} \\
 \omega_{d3} &= 0.4991 \text{ rad/s} \\
 b_{d1} &= 3,920 \text{ N/(m/s)} \\
 b_{d2} &= 3,847 \text{ N/(m/s)} \\
 b_{d3} &= 3,457 \text{ N/(m/s)}
 \end{aligned}
 \tag{8}$$

where the indexes are referred to Figure 2.7.

The simulation run lasts 22,000 sec (4 orbits). All the environmental and gravitational perturbations such as air drag, thermal perturbations, and J_2 gravity term are acting upon the system.

Figure 2.8(a) shows the temperatures, which are equals, of the three tether segments vs. time. The initial tether temperature is still slightly higher than the steady-state value but the simulation is long enough for the system to reach a thermal steady state after two orbits.

Figure 2.8(b) shows the variation of the atmospheric density over the four orbits caused by the Earth oblateness and by the variation of the local exospheric temperature (diurnal bulge). The latter effect, which has orbital frequency, seems to be dominant.

Figure 2.8(c) depicts the front, side, and longitudinal components of the acceleration on board the station. The front component is primarily generated by air drag. The side component is negligible. The longitudinal (along the tether) component shows a low frequency component generated by J_2 and the usual thermal spikes. The peak-to-peak fluctuations are about $8 \times 10^{-7}g$.

Figure 2.8(d) depicts the front and side components of the acceleration on board the elevator. Figure 2.8(e), finally, shows the

longitudinal component of the acceleration on board the elevator. The peak-to-peak fluctuations on board the elevator are about 2×10^{-5} g which means that the acceleration fluctuations with respect to the dc value (sometimes called the g-quality) are about 10^{-5} g.

2.5 Tethered Dynamic Absorber

The acceleration level at the stationary laboratory attached to the station is significantly affected by the structural vibrations of the space station. Since the microgravity experiments are most sensitive to low frequency disturbances, flexural oscillations of the single boom station are potentially a major source of acceleration noise. The frequency of the first flexural harmonic of the station is equal to 0.1 Hz for the 3-m-truss and 0.2 Hz for the 5-m-truss space station. The first flexural harmonic is of particular importance because the trough of the deformed transverse boom coincides with the location of the stationary gravity laboratory.

The magnitudes of the expected maximum amplitudes of the station's flexural modes have not been computed thus far. For the sake of our computations we have assumed a 10^{-2} m maximum deflection for the first flexural mode. The maximum values of acceleration consistent with the above amplitude are 4×10^{-4} g for the 3-m-truss and 1.6×10^{-3} g for the 5-m-truss station. It is clear from these values of accelerations that the abatement of the first flexural mode of the station is of fundamental importance for microgravity experiments. A $\approx 10^{-3}$ g level at $\approx 10^{-1}$ Hz is strong enough to disrupt microgravity processes such as protein crystal growth, vapor crystal growth, and solution crystal growth [2].

These considerations prompted us to investigate the capability of a tethered system in damping the first flexural mode of the station. Specifically the bobbing mode of the tethered system can be used to attenuate or damp the flexural mode. The system under investigation is formed by the station vibrating according to the first flexural mode in the vertical plane, a tether and an end-platform [see Figure 2.9(a)].

This system is a 2-DOF system which can be reduced to a classic two masses, two springs oscillating system [see Figure 2.9(b)].

We start by computing the equivalent mass of a point mass space station which vibrates with the same energy, frequency, and amplitude of the first flexural mode of the station. We assume that the station is a homogeneous beam of length L vibrating freely. After equating the energies of the two systems with equal maximum oscillation amplitudes we finally obtain

$$M_{EQ} = 0.757 M_s \quad (9)$$

Since the frequencies of the two systems are also the same we have that the stiffness of the first spring of the equivalent system [see Figure 2.9(b)] is:

$$k_1 = M_{EQ} \omega_1^2 = 0.757 M_s \omega_1^2 \quad (10.1)$$

and the stiffness of the second spring is

$$k_2 = M_p \omega_2^2 \quad (10.2)$$

The equations of motion of the equivalent system of Figure 2.9(b) can be found in any book of dynamics of multi-DOF systems. In particular the displacement of the equivalent station M_{EQ} and the end-mass M_p are respectively given by:

$$z_1 = \frac{F}{k_1} \left[1 - \left(\frac{\omega}{\omega_2} \right)^2 \right] / D + \frac{F_G}{k_1} \quad (11.1)$$

$$z_2 = \frac{F}{k_1} / D + F_G \frac{k_1 + k_2}{k_1 k_2} \quad (11.2)$$

$$D = \left[1 + \tau \left(\frac{\omega_2}{\omega_1} \right)^2 - \left(\frac{\omega}{\omega_1} \right)^2 \right] \left[1 - \left(\frac{\omega}{\omega_1} \right)^2 \right] - \tau \left(\frac{\omega_2}{\omega_1} \right)^2 \quad (11.3)$$

where F_G is the gravity gradient force, which is assumed to be static, $F = \cos(\omega t)$ is a generic perturbation force, $\tau = M_p / M_{EQ}$ is the mass

ratio, ω_1 is the angular frequency of the station and ω_2 of the end-platform.

For $\omega_2 = \omega$ the oscillation of the station ceases. The tethered system acts as a dynamic absorber. In this case the displacement of the end-mass is

$$z_2 = -\frac{F}{k_1} \left(\frac{\omega_1}{\omega_2} \right)^2 / \tau + \frac{F_G}{k_1} \left[1 + \left(\frac{\omega_1}{\omega_2} \right)^2 \right] / \tau \quad (12)$$

where $F/k_1 = \xi_{SF}$ and F_G/k_1 are simply the static deflections associated with the forces F and F_G . It seems, therefore, that a tether system can in principle attenuate the first flexural mode of the station and that it can be easily tuned to the desired frequency by simply varying the steady-state tether length. In reality the avoidance of tether slackness poses a strong constraint to the design of a tethered dynamic absorber.

The tether tension T [see Figure 2.9(b)] is proportional to $z_2 - z_1$. Hence for $T = 0$ and for a dynamic absorber with $\omega_2 = \omega$ equations (21) yield:

$$[z_2 - z_1] \omega = \omega_2 = \frac{F_G - F}{k_1} \left(\frac{\omega_1}{\omega_2} \right)^2 / \tau = 0 \quad (13)$$

where

$$F_G = 3M_p \Omega^2 l \quad (14)$$

In equation (14) l is the tether length and M_p is the effective mass of the tethered system which takes into account the tether mass and the platform mass as follows [4]: $M_p = M_{p0} + 1/2 \mu l$ where M_p is the mass of the platform and μ the linear density of the tether. From equation (13) we compute the minimum effective static moment $M_p l$ which provides a null tether tension. From equations (10.1), (13) and (14) we obtain

$$M_{pl} = \frac{0.757}{3} \zeta_{SF} M_S \left(\frac{\omega_1}{\Omega} \right)^2 \quad (15)$$

where ζ_{SF} is the amplitude of the oscillations (i.e. non related to gravity gradient) of the station's first flexural mode. It is worth noticing that the minimum effective static moment M_{pl} is independent of the frequency $\omega = \omega_2$

An important example is the utilization of the dynamic absorber for damping the station first flexural mode at the resonant frequency ω_1 . In this case the bobbing frequency of the tethered vibration absorber ω_2 is tuned to ω_1 and therefore $EA = \omega_1 M_{pl}$ where EA is the tether stiffness. The tether linear density μ is also related to the tether cross section A and to the volume density ρ by: $\mu = \rho A$.

For a tether of given intrinsic characteristics E and ρ we can therefore evaluate the mass of the platform M_{po} and the tether linear density μ as a function of ω_1 and of ζ_{SF} by means of equation (15). For a numerical example we adopt an oscillation amplitude of the station $\zeta_{SF} = 10^{-2}$ m, and an orbital rate $\Omega = 1.14 \times 10^{-3}$ rad/s (orbital altitude = 352 km).

Figure 2.10(a) shows the effective static moment M_{pl} vs the frequency $f_1 = \omega_1/(2\pi)$. For the resonant frequency of the proposed configuration of the single-boom station (around 0.1 Hz) the minimum effective static moment must be at least 10^8 kg-m. If we adopt a kevlar tether with $E = 6.2 \times 10^{10}$ N/m² and $\rho = 1440$ kg/m³, the tether diameter $d = 28.5$ mm. For a steel tether with $E = 20 \times 10^{10}$ N/m² and $\rho = 8 \times 10^3$ kg/m³, we obtain $d = 15.8$ mm.

Figures 2.10(b) shows the mass of the platform, of the tether, and the total mass of the absorber respectively for kevlar or steel tethers. The numerical results point out that a tethered dynamic absorber for the station is quite massive. Convenient tether lengths range between 5 and 10 km with total masses ranging from 24 to 14.6 metric tons. Kevlar tethers are more convenient from a mass point of view. For a 10-km-long kevlar tether, for example, $M_{po} = 5400$ kg, $m_T = 9200$ Kg

and the total mass of the dynamic absorber M_{TOT} is 14,600 kg. For a 10-km-long steel tether we have, instead, $M_{po} = 2110$ kg, $m_T = 15,780$ kg and $m_{TOT} = 17,890$ kg.

The dynamic absorber is purely passive. Its ability to attenuate the flexural oscillations of the station is based upon an energy transfer from the vibrating station to the absorber which is maximized when the device is tuned to the frequency to be abated. That energy however remains in the absorber unless a damping mechanism is added to the system. The additional damper may simply be implemented by controlling the tether length with a proportional derivative control law or by inserting a spring-dashpot system between the station and the tether. The mathematics of the system becomes more complex but its analysis does not add much to the design of the absorber except for the additional computation of the damper's damping coefficient.

One final concern. Since the tethered dynamic absorber is massive, it causes a non-negligible shift of the overall system CM and hence a non-negligible dc value of the acceleration at the stationary gravity laboratory. A dynamic absorber with a 10^8 kg-m static moment produces a CM shift of 500 m which corresponds to a dc acceleration of 2×10^{-4} g. In order to neutralize this effect an equal-static-moment tethered system should be deployed on the opposite side of the station. The two systems together form a Double Tethered Centered System (DTCS) with dimensions somewhat different from the DTCS described in Section 2.4.2. The tethered system opposite to the dynamic absorber should be detuned from the flexural modes of the station. A lower bobbing frequency (tether softer and thinner than the dynamic absorber's tether) is recommended so that the vibrations of the station are attenuated before reaching the end-platform (on this subject see also reference [5] for further detail).

2.6 Concluding Remarks

The analysis carried out on the proposed tethered systems for the active control of the center of gravity of the space station shows that all the three configurations meet the microgravity requirement (10^{-5} g) for the acceleration level on board the station. Specifically in order to meet that requirement over a large number of orbits each system must be equipped with longitudinal dampers in series with the tether segments. Each damper may simply be a spring-dashpot system (the dampers' stretches for the three systems are at most a few-centimeter-long) tuned to the bobbing frequency of the associated tether segment. The dampers rapidly abate the longitudinal tether oscillations excited by thermal shocks ensuing the crossings of the terminator.

The tether-related acceleration noise on board the station for the three tether systems is generated primarily by thermal shocks. On the other hand, the air drag, which is responsible for the front component of the acceleration, is mainly related to the frontal area of the station while the contributions of the tethers' cross sections are marginal.

If longitudinal dampers are adopted the maximum acceleration level on board the station for the Double Tethered System with and without the Elevator is less than 10^{-6} g. The performance of the Single Tether System with respect to tether-related acceleration noise is even better since the maximum fluctuations of the longitudinal acceleration component around the *dc* value are of the order of 10^{-8} g. A light and short tethered system is, in fact, less influenced by thermal shocks.

Finally the acceleration fluctuations (g-quality) on board the elevator of the Double Tethered System are about 10^{-5} g.

In conclusion the acceleration levels on board the station for the three proposed configurations are well within the 10^{-5} g requirement if longitudinal dampers are added to these systems. The g-quality on board the elevator for the Double Tether System with Elevator is

comparable to the g-quality of the microgravity laboratory attached to the station.

From previous experience the tether-related acceleration noise on the station and the elevator can be further improved if softer tethers are used. This implies the usage of tether materials with moderate values of the Young modulus and moderate tether diameters. Since the selection of the tether diameter is driven by the survivability of the tether to micrometeoroid impacts, the evaluation of the probability of tether failure must be carefully estimated in order not to oversize the tethers.

A Tethered Dynamic Absorber can abate the space station's first flexural mode. However, for a modal frequency of 0.1 Hz (3-m-truss station) and a modal amplitude of 10^{-2} m the total mass of a 10-km-long kevlar-tether dynamic absorber is about 14.6 metric tons in order to avoid tether slackening. Since this system has a strong static moment it requires a compensating tethered system on the opposite side of the station. The end result is a Double Tethered System in which one side, tuned to the flexural mode of the station, is the Dynamic Absorber, while the other side is detuned from the flexural oscillations.

For frequencies lower than 0.1 Hz the mass required for a Dynamic Absorber decreases strongly because the minimum static moment is inversely proportional to the square of the frequency. It seems therefore that a Dynamic Absorber becomes much more desirable if it will be proven that low frequency (< 0.1 Hz) flexural oscillations are excited during the mission of the single-boom space station.

2.7 References to Section 2

- [1] Cosmo, M., E.C. Lorenzini, S. Vetrella and A. Moccia, "Transient Dynamics of the Tether Elevator/Crawler System," Proceedings of the 1988 AIAA/AAS Astrodynamics Conference, Minneapolis, MN, 15-17 August 1988.
- [2] Sharpe, A. (Ed.), "Low Acceleration Characterization of Space Station Environment," Teledyne Brown Engineering, Final Report for NASA/MSFC Contract NAS8-36122, Mod. 6, October 1985.
- [3] Timoshenko, S., D.H. Young, W. Weaver Jr., "Vibration Problems in Engineering," John Wiley and Sons.
- [4] Baker, W.P., et al., "Tethered Subsatellite Study," NASA TMX-73314, March 1976.
- [5] Gullahorn, G.E. and R.G. Hohlfeld, "Tether as a Dynamic Transmission Line," Space Tethers for Science in the Space Station Era, L. Guerriero and I. Bekey (Eds.), Societa' Italiana di Fisica, Conference Proceedings, Vol. 14, Bologna, Italy, 1988, pp. 163-168.

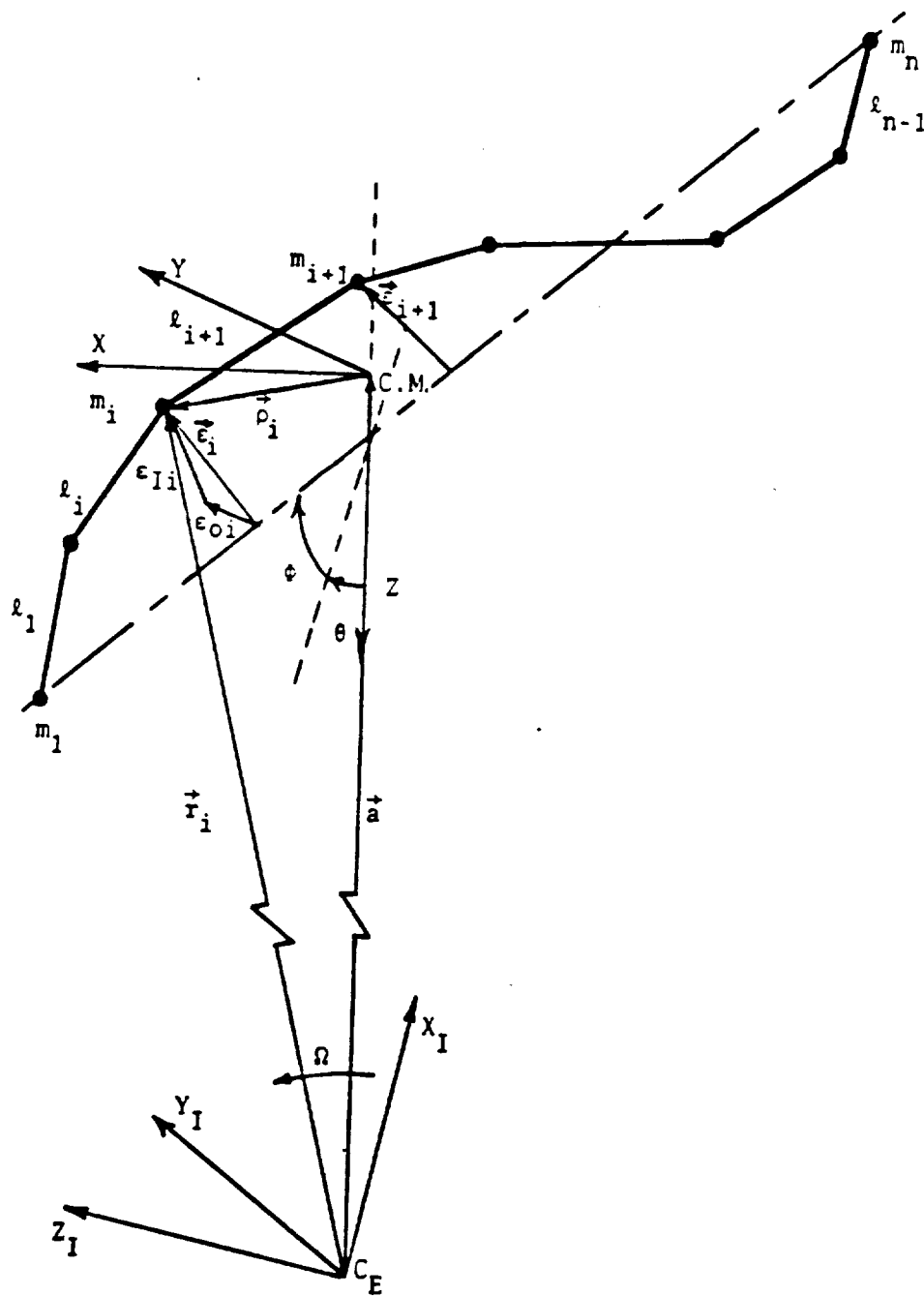
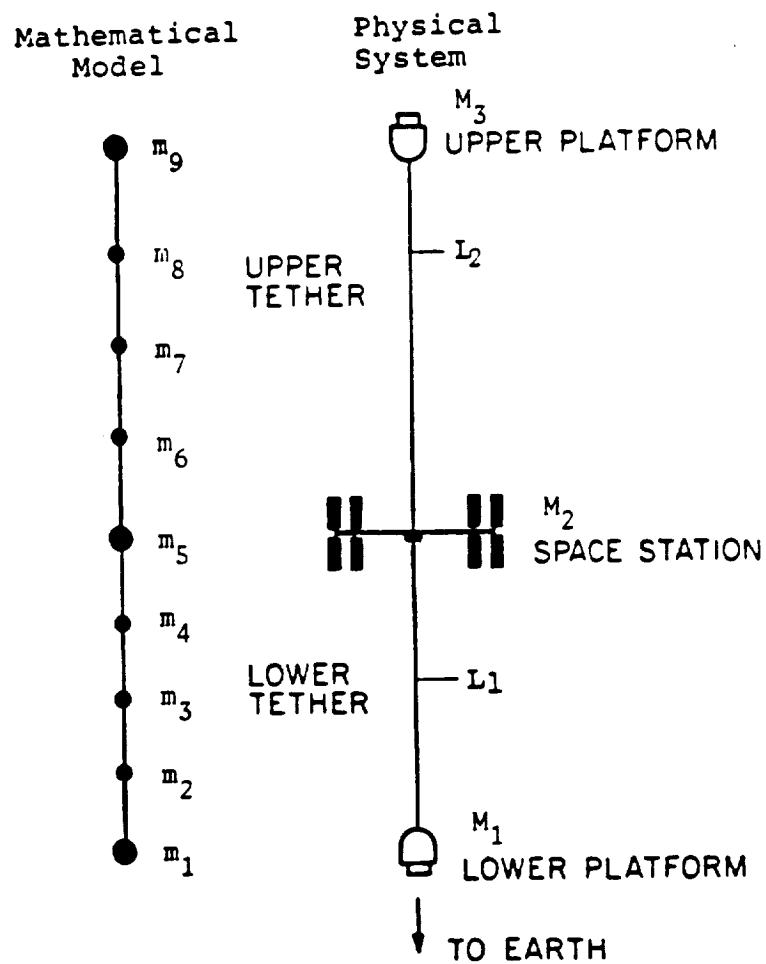
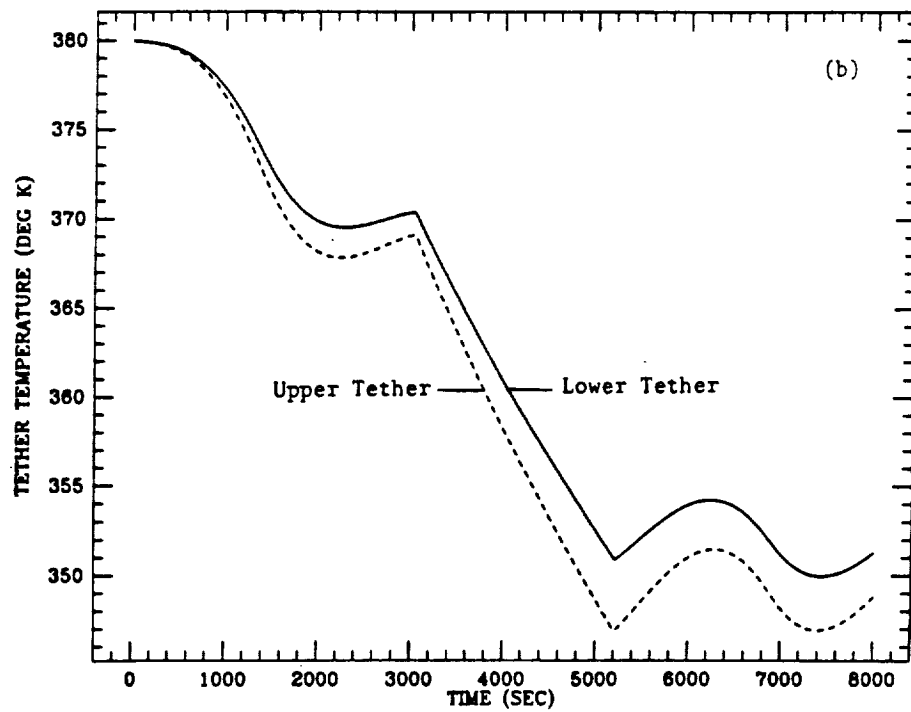
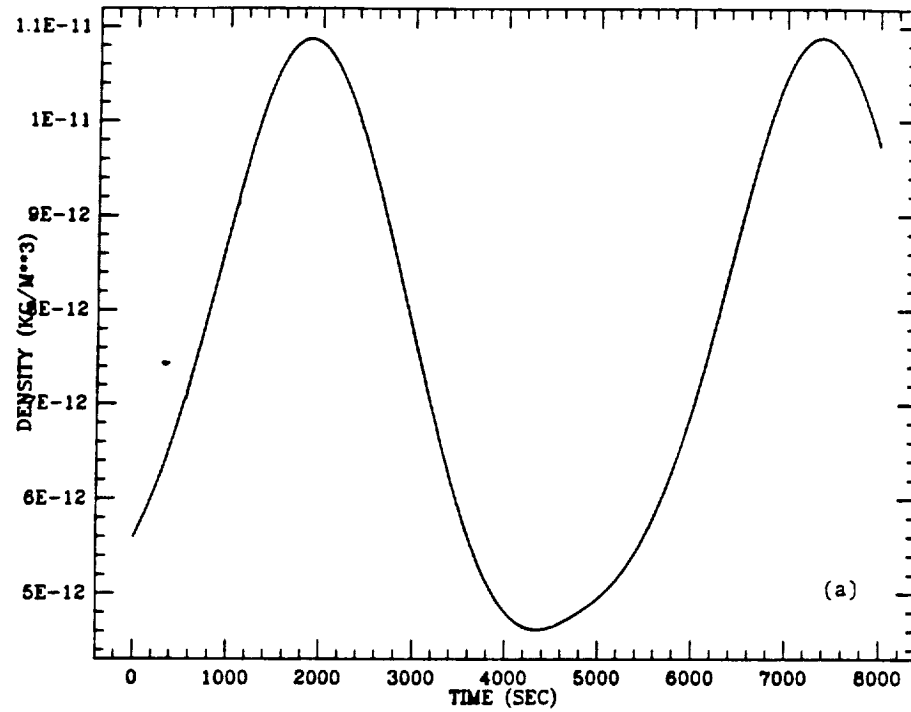
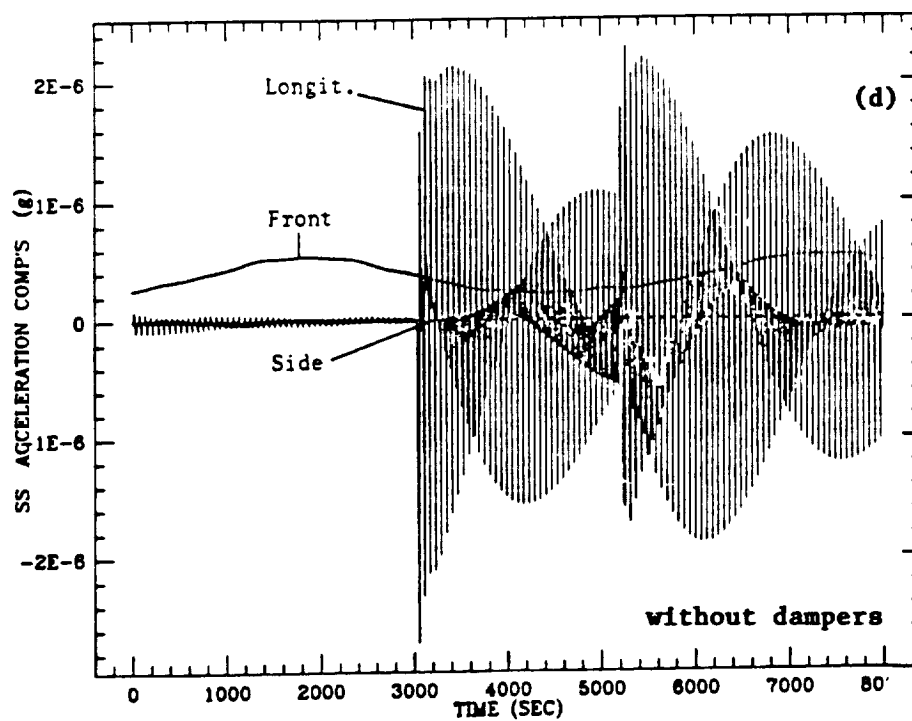
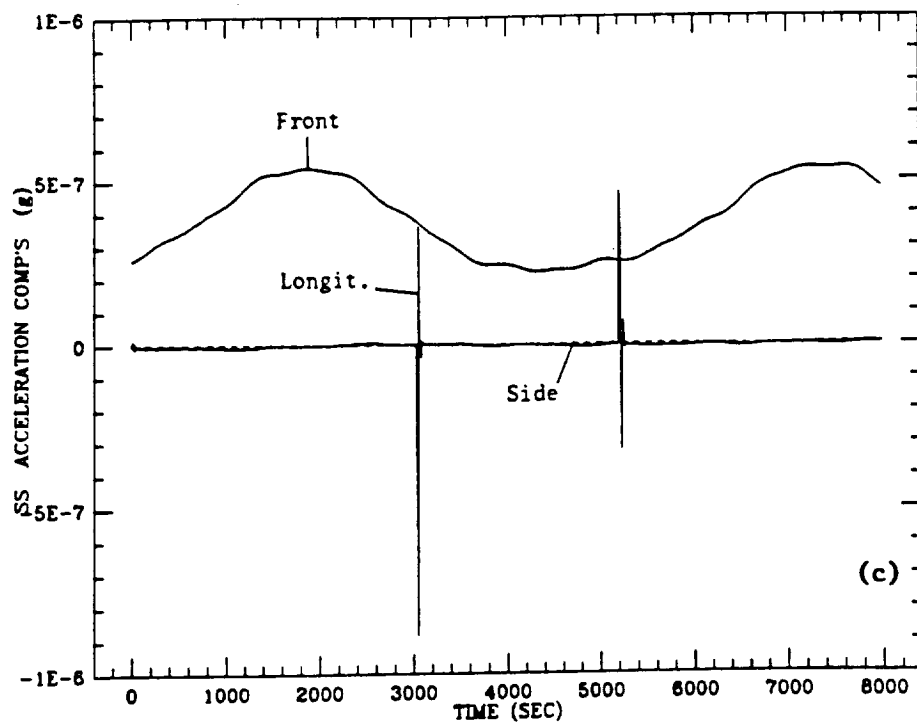


Figure 2.1

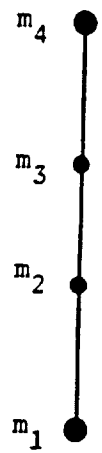
Double Tether Centered System (DTCS)**Figure 2.2**



Figures 2.3(a)-(b)



Figures 2.3(c)-(d)

Single Tether System (STES)Mathematical
Model

Physical Model

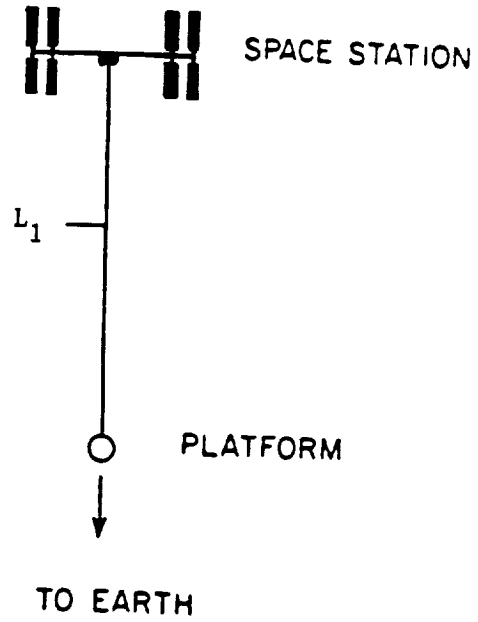
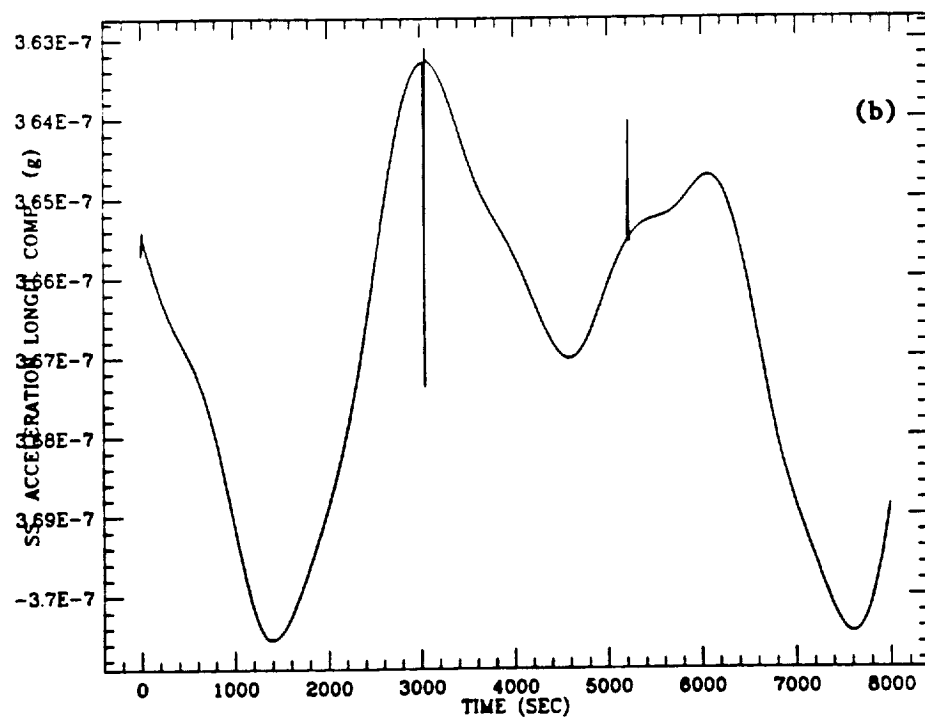
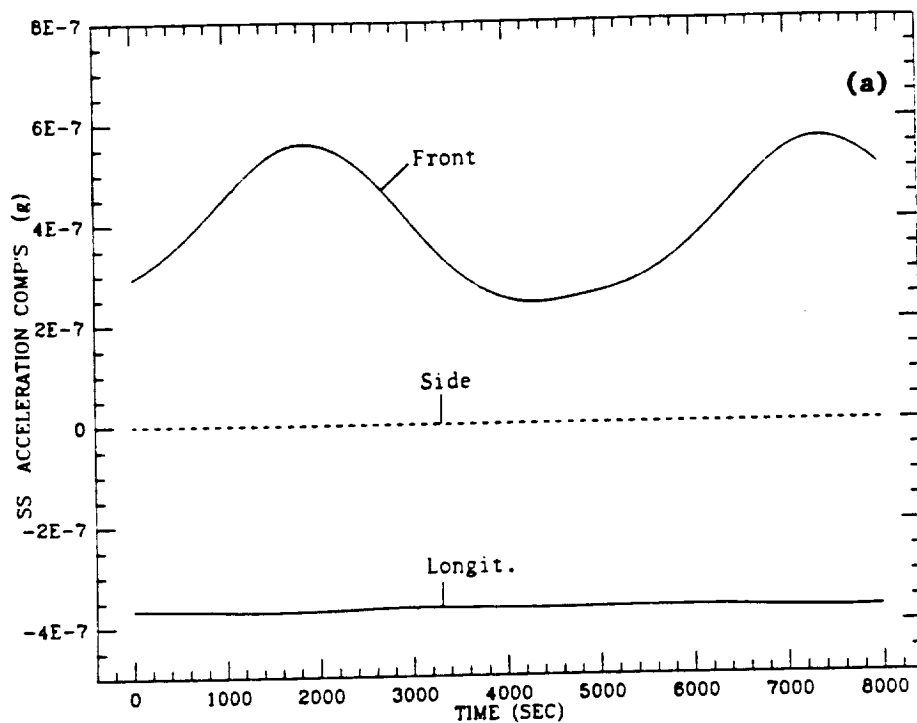


Figure 2.4

**Figures 2.5(a)-(b)**

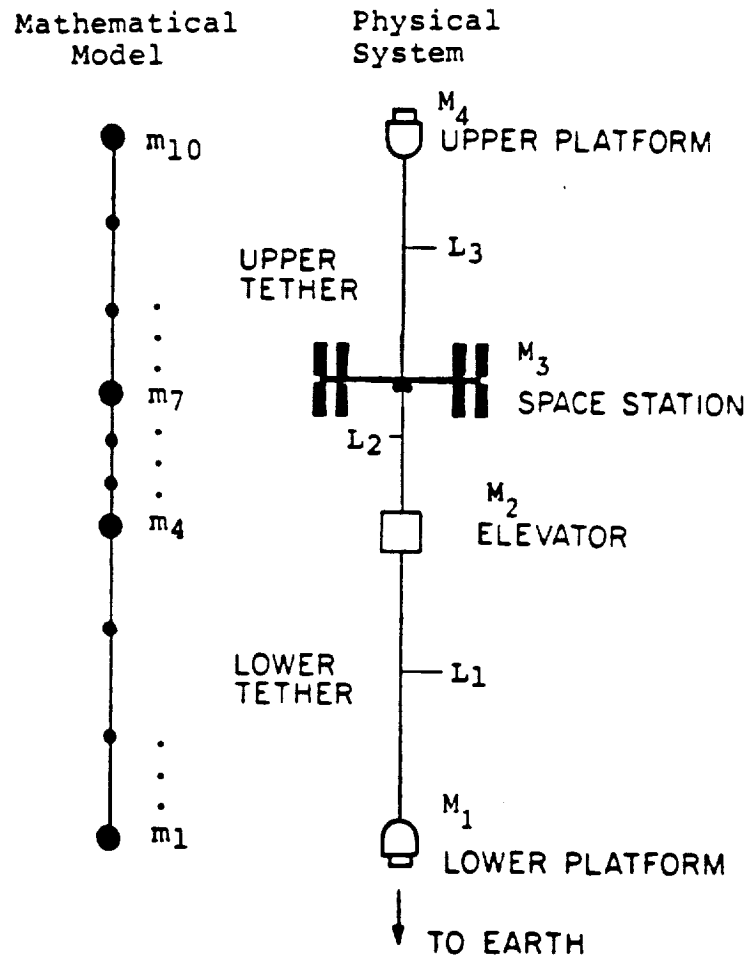


Figure 2.6

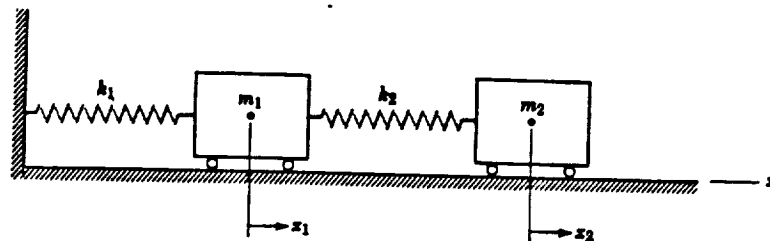
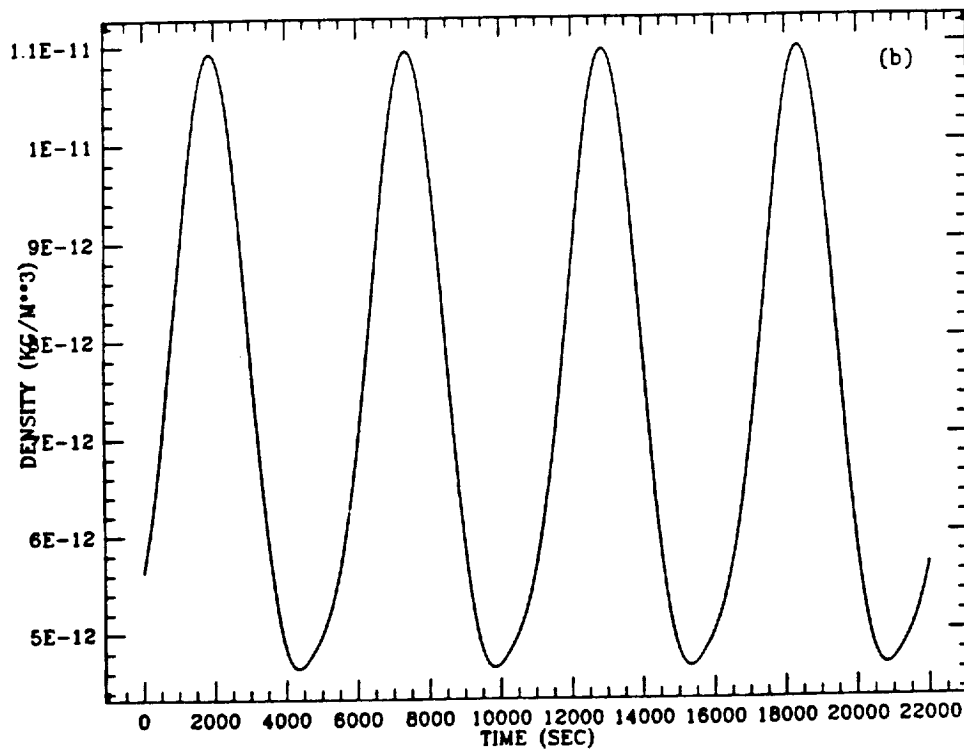
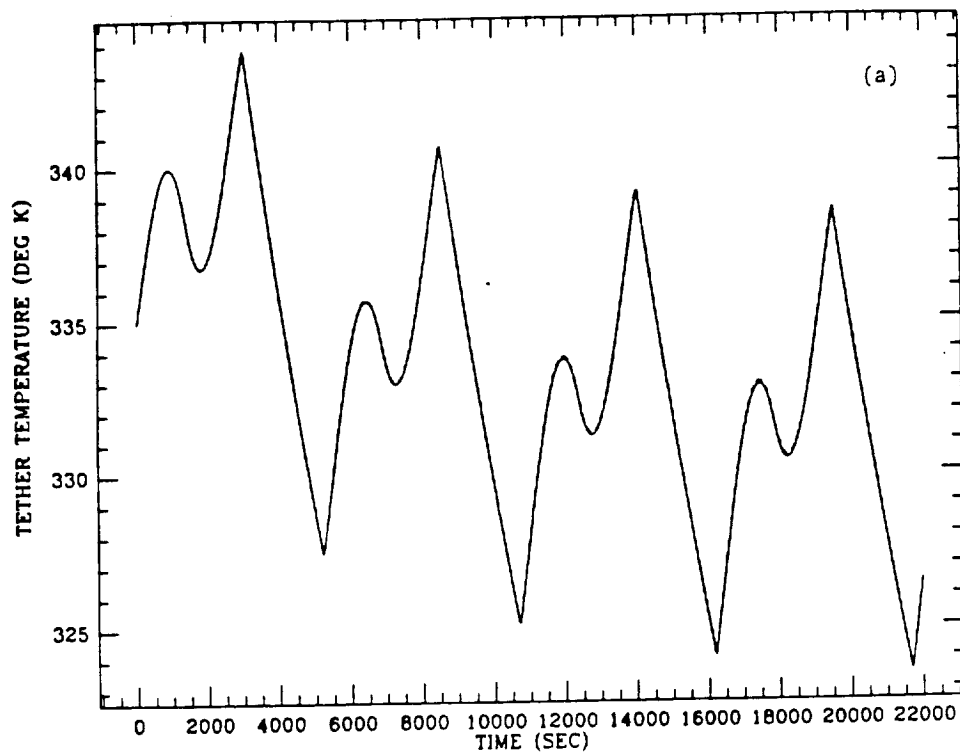
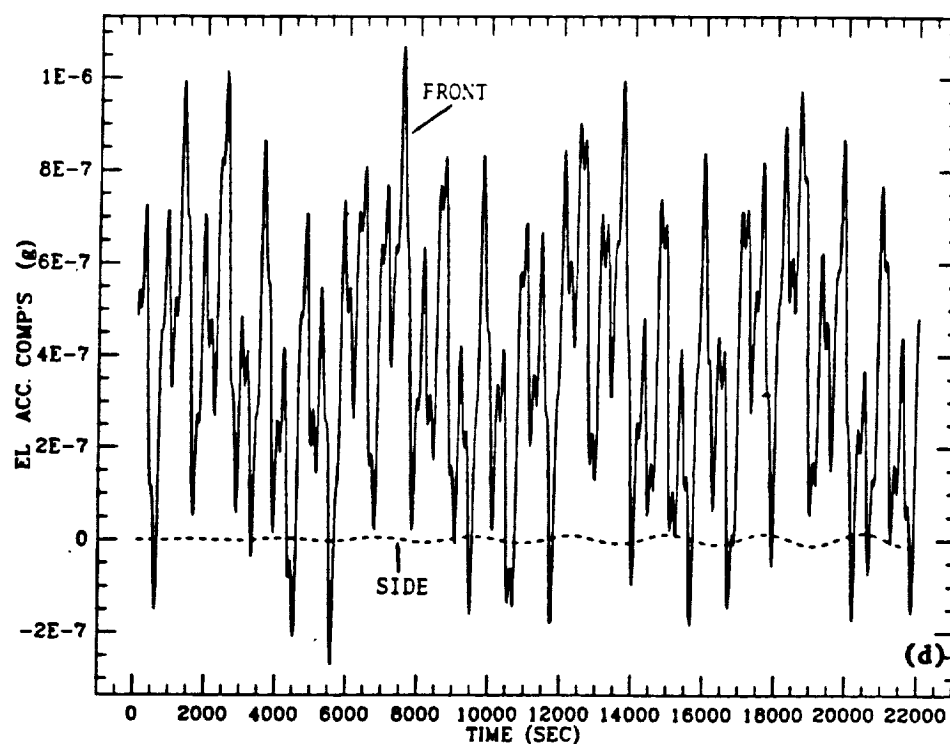
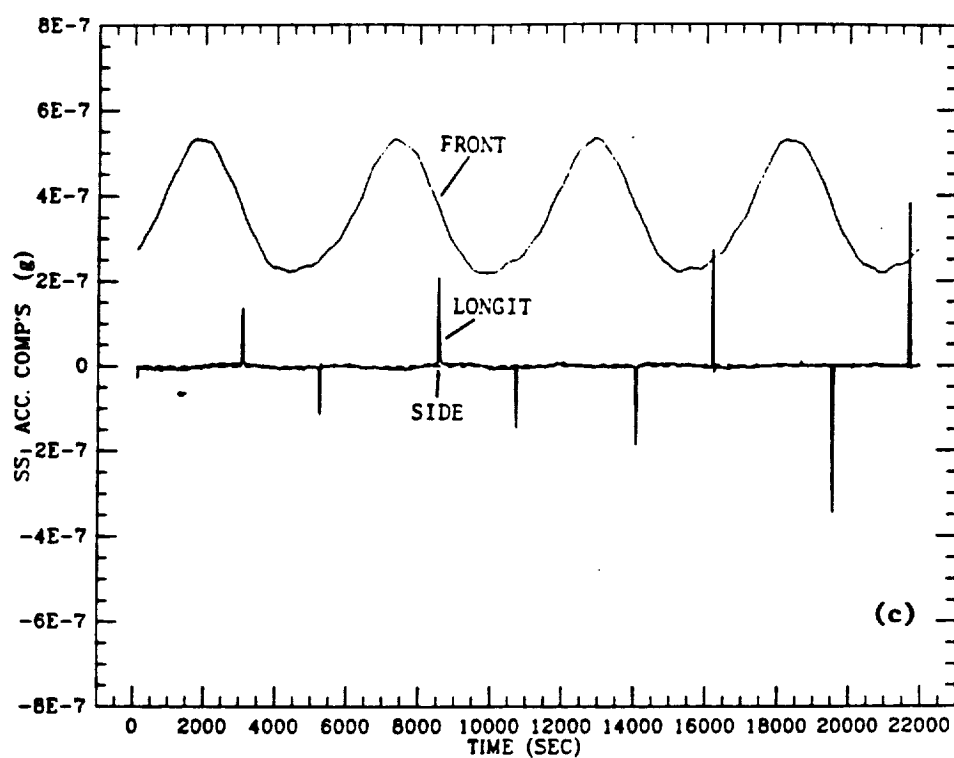


Figure 2.7

**Figures 2.8(a)-(b)**

**Figures 2.8(c)-(d)**

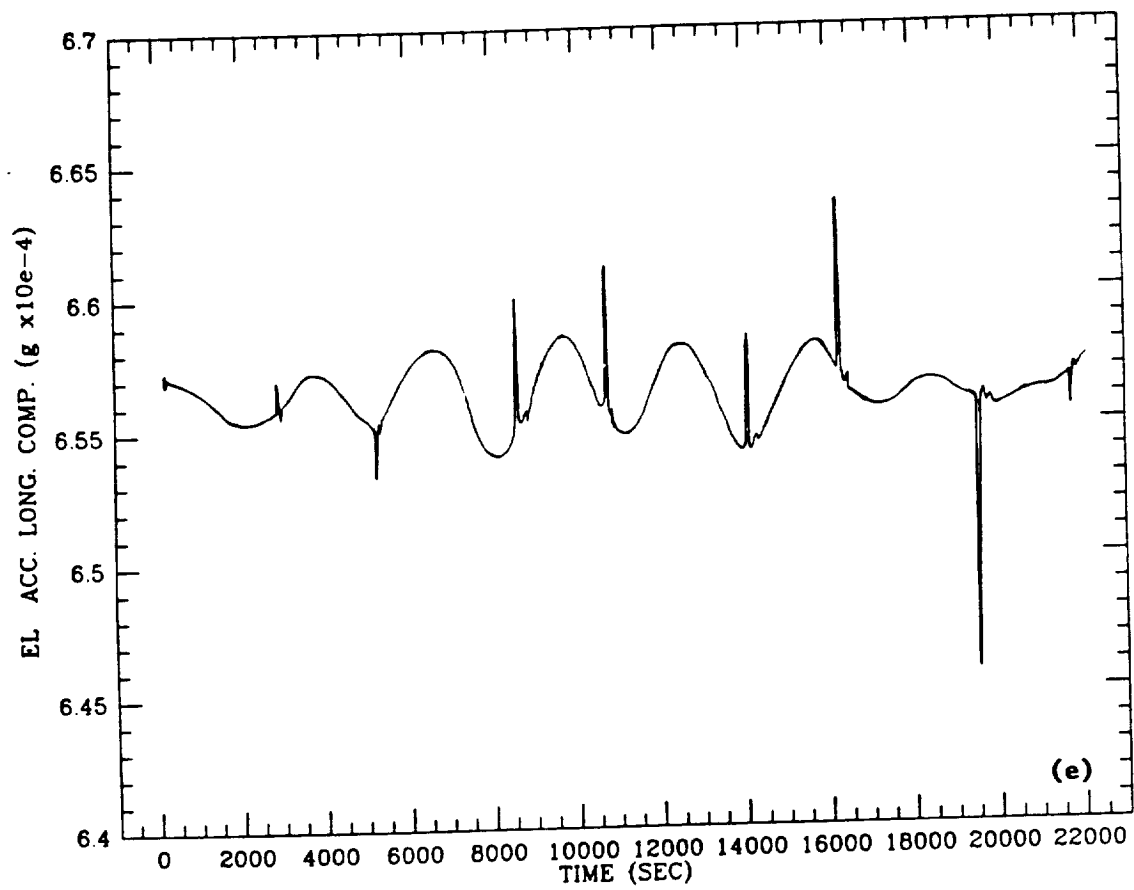
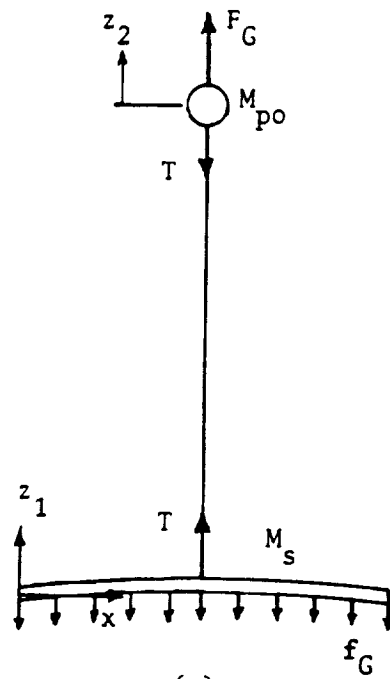


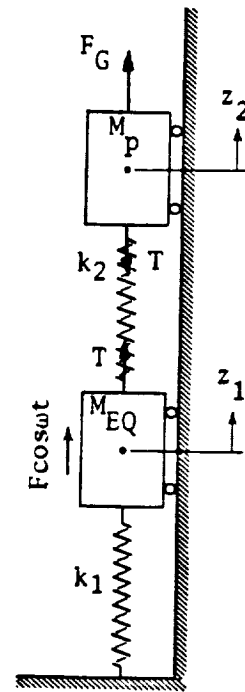
Figure 2.8(e)

Physical System



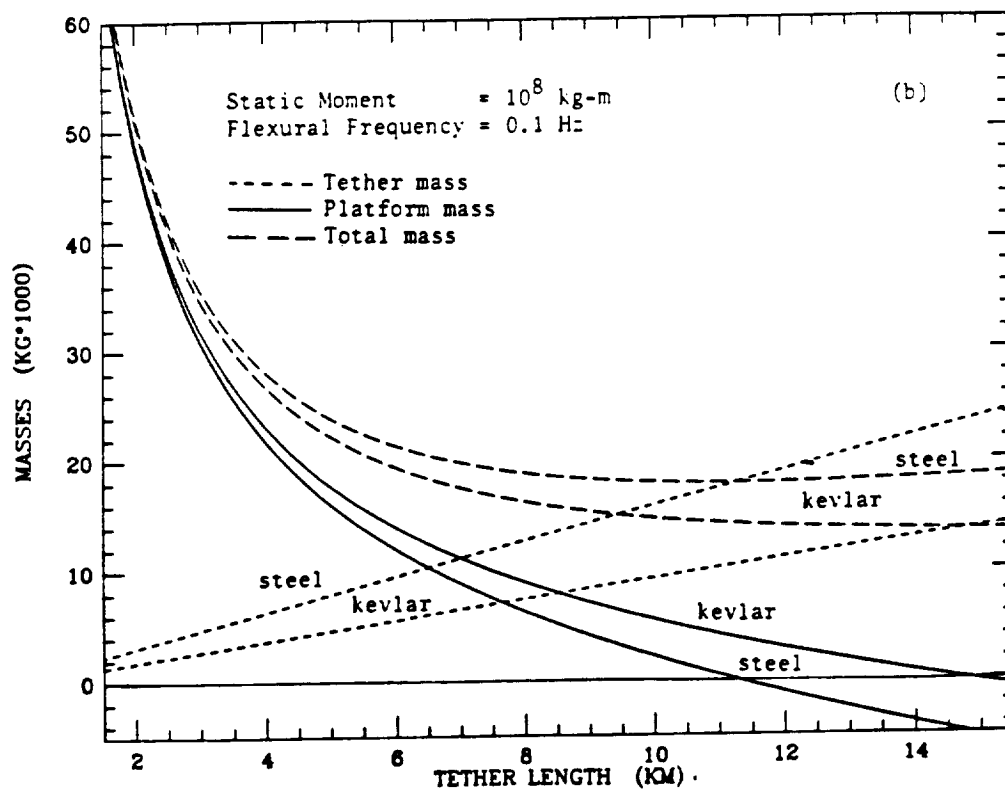
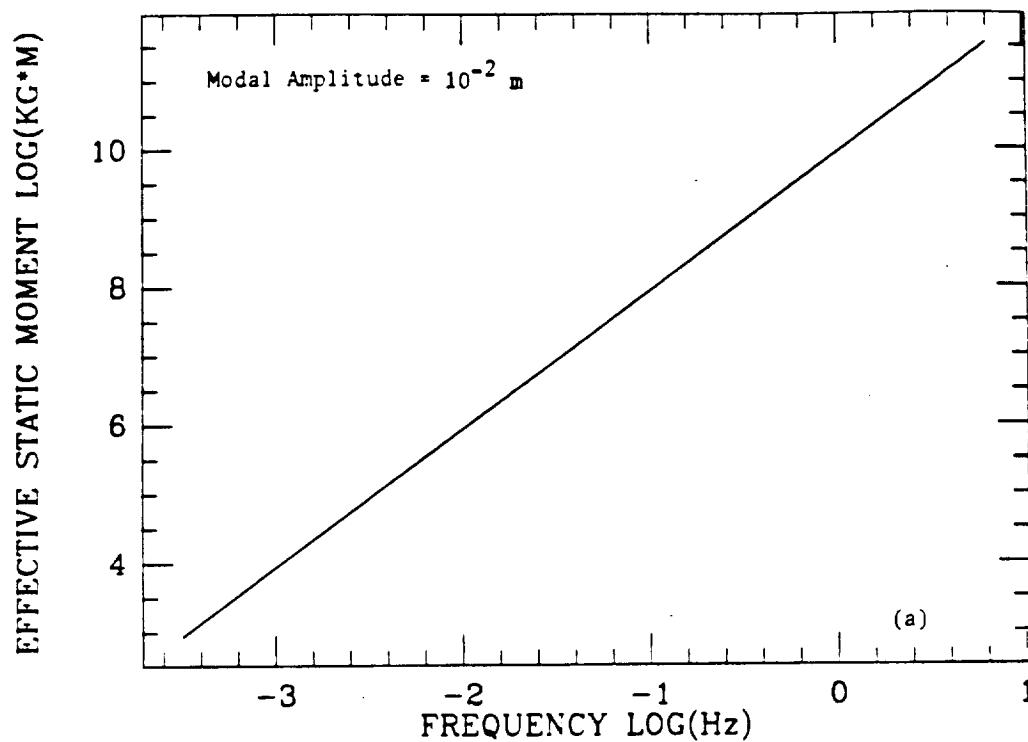
(a)

Equivalent Model



(b)

Figures 2.9(a)-(b)



Figures 2.10(a)-(b)

3.0 VARIABLE GRAVITY LABORATORY

3.1 Introductory Remarks

The variable gravity laboratory (VGL) is a system designed to explore a range of "unperturbed" acceleration levels from 0 g to 4×10^{-3} g. The system makes use of a tethered space elevator to achieve the desired acceleration level by moving the elevator to a point along the tether where the gravity gradient is equal to the desired acceleration level. More specifically one of the requirements from the microgravity scientific community is to explore "unperturbed" acceleration levels as follows: 0 g, 5×10^{-6} g, 10^{-5} g, 5×10^{-5} g, 10^{-4} g, 5×10^{-4} g, 10^{-3} g, 4×10^{-3} g. The experimental samples will be exposed for a long time (i.e. several days) to each one of these acceleration levels. The samples will also be disactivated during the transfer maneuvers of the elevator. Consequently the requirements for the acceleration profile during the transfer maneuvers are relaxed so long as the dynamic stability of the system is not impaired and the acceleration noise transmitted to the station is not unreasonably high.

Based upon considerations of operational simplicity and engineering constraints Aeritalia has decided to adopt a single tether system as a baseline for the variable gravity laboratory. The VGL will be deployed toward the Earth, as shown in Figure 3.1. The major design parameters are as follows:

Orbital height	= 352 km
Orbital inclination	= 28.5°
M_1	= 2794 kg
M_2 (VGL)	= 2000 kg
M_3 (SS)	= 204.5×10^3 kg
L	= 10500 m, kevlar tether, 10 mm diameter

$$\begin{aligned}
 EA &= 1,541,125 \text{ N} \\
 EA' &= 53156 \text{ N-sec} \\
 m_T &= \text{tether mass} = 1187.5 \text{ kg}
 \end{aligned}$$

A single tether system, like the one under investigation, is simpler than a double tether system. On the other hand, a single tether system can not compensate neither for the displacement of the elevator nor for the steady acceleration level on the station when the elevator is stationary. Consequently the acceleration level on board the station increases as the elevator moves farther away from the station. The acceleration levels might exceed the microgravity level required for the station for position of the elevator near the tether tip. This tethered system, however, is not intended to be a permanently deployed facility and the violation of the acceleration levels on the station will be confined to the time when the VGL is deployed. Nevertheless the compatibility of the operations of a variable gravity single-tether laboratory with the station's mission profile and microgravity requirements should be verified with the space station's program office before designing the hardware of a single-tether variable gravity laboratory.

3.2 Elevator's Motion Control Laws

The crawling is used to perform low gravity experiments at different g-levels regardless of the acceleration profile during the transient phases. Consequently the crawling time plays a major role in the choice of the control law. Moreover, care must be taken in damping out the perturbations excited by the acceleration and deceleration phases.

A control law suitable for our purposes is the Mirror Image Motion Control Law (MIMCL), developed at SAO and Tri-State University [1, 2, 3]. This law has been successfully tested at Tri-State University, Angola, Indiana with the crawler system built by Prof. Frank R. Swenson [4].

MIMCL has been developed to meet the following requirements:

- Acceleration and deceleration phases as smooth as possible
- Small perturbations of the system dynamics

MIMCL consists of three separate phases namely: (a) acceleration phase, (b) constant velocity phase, and (c) deceleration phase. In terms of variation of travelled tether lengths the control law for the Elevator's motion can be expressed as follows:

$$\begin{aligned}
 \text{a)} \quad \Delta l_c &= \Delta l'_c [\tanh(\alpha t)]^\gamma & t < t_A \\
 \text{b)} \quad \Delta l_c &= \Delta l'_c [\tanh(\alpha t_A)]^\gamma + \Delta l''_c \frac{t - t_A}{t_B - t_A} & t_A \leq t \leq t_B \\
 \text{c)} \quad \Delta l_c &= \Delta l_{cT} - \Delta l'_c [\tanh[\alpha(t_T - t)]]^\gamma & t_B \leq t \leq t_T
 \end{aligned}$$

where

$$t_A = \frac{1}{2} \sinh^{-1}(\sqrt{(\gamma-1)/2}) \quad = \text{time when the maximum velocity } V \text{ is reached}$$

$$t_B = t_A + \Delta l''_c / V$$

$$t_T = t_A + t_B$$

$$V = \Delta l'_c \propto \frac{2\gamma}{\gamma+1} \left(\frac{\gamma-1}{\gamma+1} \right)^{(\gamma-1)/2} \quad = \text{maximum and constant velocity}$$

- Δl_{CT} = total variation of travelled length
 $\Delta l'_c$ = length travelled at constant speed
 $\Delta l'$ = length of the hyperbolic tangent

$$\text{phase} = \frac{(1-Y)}{2 \left(\sqrt{(\gamma-1)/(\gamma+1)} \right)^\gamma} \Delta l_{CT}$$
 Y = Fraction of the total length travelled at constant velocity

MIMCL is a function, for a given Δl_{CT} , of the parameters α , γ and Y where α = rate parameter, γ = shape parameter, and Y = constant-velocity-phase parameter. In reference [1] it is shown how the constant velocity phase reduces the total crawling time compared to a simple hyperbolic function control law. The maximum acceleration, excited by the Elevator's motion, is minimized for $Y = 0.664$. In reference [1] it is also shown that the maximum amplitude of the acceleration reaches a lower limit for $\gamma = 5$.

Thus by setting $\gamma = 5$ and $Y = 0.664$, MIMCL is a function of the time constant α only. A high value of α causes the following phenomena:

- a) motion-induced accelerations becomes too high to be rapidly damped out,
- b) large Coriolis forces may require active control of the system librations and transverse oscillations,
- c) total travel time decreases as α increases.

The right choice of the value of α stems from a trade-off between the travel time and the excitation of undesired oscillations.

The g-levels on board the VGL scale with the distance between the orbital center and the VGL as shown in Table 1. In the same table

the g-levels experienced on board the Space Station are also shown. For the sake of brevity we will examine in this section two crawling maneuvers only, namely: (a) from 0 g to 5×10^{-6} g, and (b) from 10^{-3} g to 4×10^{-3} g. This does not limit the generality of the investigation since (a) and (b) are extreme cases.

Let us consider first the crawling from 0 g to 5×10^{-6} g. The travelled distance is 13 m, neglecting the tether elasticity, that in this case is only a few centimeters long. Since the travelled distance is small it is reasonable to complete the crawling in a short time. On the other hand also the motion-induced accelerations should be reasonably small. We have explored values of the time constant $1/\alpha$ equal to 250 s, 500 s, and 1000 s which correspond to crawling times of 18 min, 35 min and 70 min. respectively. The variation of the travelled distance vs. time is shown in Figure 3.2(a). The crawling velocity is shown in Figure 3.2(b). Note that for $1/\alpha = 250$ the maximum velocity of 1.6×10^{-2} m/sec is within the capabilities of the Aeritalia's crawler system of 1 m/sec [5]. The g-profiles corresponding to the three different crawling maneuvers are shown in Figure 3.2(c). The absolute values of the Coriolis acceleration are shown in Figure 3.2(d) and the crawling-induced accelerations are shown in Figure 3.2(e). Note that for $1/\alpha = 250$ sec the peak of the Coriolis acceleration is of the same order of magnitude of the final acceleration.

In conclusion $1/\alpha = 500$ sec appears to be a good trade-off value for short distance maneuvers.

Let us consider now the crawling maneuver (b) from 10^{-3} g to 4×10^{-3} g corresponding to a travelled distance of 7575 m. In this case, since the travelled distance is large, the major concerns are: the Coriolis force, the maximum crawling velocity, and the total crawling time.

Since the maximum velocity of VGL is 1 m/sec, a travelled distance of 7575 m asks for $1/\alpha \geq 2550$ sec. The travelled distances for $1/\alpha$ equal to 2550 sec, 2750 sec, and 3000 sec, corresponding to crawling times of 3 hrs, 3.23 hrs and 3.52 hrs respectively, are shown

in Figure 3.3(a). The corresponding crawling velocities are shown in Figure 3.3(b), and g -profiles in Figure 3.3(c). Coriolis accelerations are shown in Figure 3.3(d). Note that for $1/\alpha = 2550$ the maximum acceleration is about $2.6 \times 10^{-4} g$.

The crawling-induced accelerations are shown in Figure 3.3(e); the maximum acceleration for $1/\alpha = 2550$ is about $7 \times 10^{-5} g$. As expected the Coriolis accelerations play an important role in this case. In conclusion $1/\alpha = 2550$ s seems a good trade-off value for long distance maneuvers.

Table 1. Gravity Levels On-Board VGL and SS vs VGL-SS Distance (l_2)

$ a_{VGL} (g)$	$ a_{SS} (g)$	$l_2 (m)$
0	5.64×10^{-5}	141
5×10^{-6}	5.64×10^{-5}	154
10^{-5}	5.65×10^{-5}	167
5×10^{-5}	5.69×10^{-5}	268
10^{-4}	5.74×10^{-5}	394
5×10^{-4}	6.12×10^{-5}	1404
10^{-3}	6.60×10^{-5}	2667
4×10^{-3}	9.49×10^{-5}	10242

3.3 Modal Vibration Dampers

By assuming small amplitudes of oscillations the vibrational modes of the VGL can be separated in the following categories:

- a) longitudinal oscillations
 - platform bobbings
 - tether vibrations
- b) transverse oscillations
 - platform vibrations
 - tether vibrations
- c) librational oscillations of the entire system

We have already pointed out that even during station-keeping phases longitudinal dampers are necessary in order to abate the longitudinal oscillations driven by thermal shocks. When the elevator moves along the tether, in-plane transverse and librational oscillations are also excited. The faster the elevator moves, the larger the perturbations. Consequently elevator's maneuvers with a long travelled length and a short duration require efficient devices for damping the excited oscillations.

The next subsections describe briefly the various types of damping devices which are utilized in the VGL to abate undesired oscillations.

3.3.1 Longitudinal Dampers

Longitudinal oscillations are subdivided into "high-frequency" tether oscillations and bobbing motions of the platforms. The former are abated by the tether material damping, the latter are damped by longitudinal dampers. Since the elastic stretch of the VGL's tether is at most 1 m long, longitudinal dampers can be passive devices. Basically they are spring-dashpot systems placed at the tether attachment points to the station and to the lower end-platform.

As already mentioned in references [3], [6], and [7] longitudinal dampers are very effective if each one is tuned to the frequency of the largest amplitude longitudinal modal component of the associated tether segment and the damping ratio of the damper is 0.9. For the VGL there is, however, one additional concern. As the elevator moves along the tether the longitudinal modal frequencies of the two tether segments vary and the passive dampers become detuned. Two options are available to solve this problem: (1) to adopt active longitudinal dampers with adaptive gains, (2) to tune the passive dampers to a longitudinal frequency which is an average between the values at the two extreme positions of the elevator along the tether. Option (1) is more effective but requires a more complex mechanization and accurate sensors to feed the tether tension, tether length, and velocity into the control systems. Option (2) is simpler but the performance of the longitudinal dampers is the more degraded the farther away the elevator is from the tuning point. Nevertheless we have opted for option (2) because of its simplicity pending the results from the dynamics analysis to confirm or disprove our choice.

By tuning the longitudinal dampers of the VGL to the longitudinal frequencies of the tether segments when the elevator is at the orbital center, the characteristic of the dampers are:

$$\begin{aligned}\omega_{d1} &= 0.18 \text{ rad/s} \\ b_1 &= 1525.12 \text{ Ns/m} \\ \omega_{d1} &= 3.06 \text{ rad/s} \\ b_2 &= 6413.77 \text{ Ns/m}\end{aligned}$$

3.3.2 Transverse Damper

Damping of the in-plane component of the transverse oscillations of the elevator with respect to the end-platforms is accomplished by moving the elevator along the tether. A motion of the elevator along the tether generates a Coriolis force, on the elevator, perpendicular to

the direction of the relative motion and to the orbital angular velocity. Consequently the Coriolis force lays on the orbital plane. If we displace the elevator with a phase such that a Coriolis force opposed to the transverse displacement is generated, the work per cycle done by the control system is negative and the in-plane transverse vibrations are damped out. The in-plane component of the transverse vibration is much greater than the almost negligible out-of-plane component. Consequently the former requires an effective damper when the elevator travels along the tether.

A control law for transverse elevator's vibrations requires the knowledge of the in-plane displacement of the elevator ϵ_I with respect to the end-platforms. In terms of variation of the natural lengths of the two tether segments the control law can be expressed as follows [6]:

$$\begin{aligned}\frac{\Delta l_1^\epsilon}{l_{02}} &= k_\epsilon \epsilon_I \\ \frac{\Delta l_2^\epsilon}{l_{02}} &= -\frac{l_{01}}{l_{02}} k_\epsilon \epsilon_I\end{aligned}$$

where Δl_1^ϵ and Δl_2^ϵ are the variations of the lengths of tether segment 1 (between the lower-platform and the elevator) and tether segment 2 (between the elevator and the station). Likewise l_{01} and l_{02} are the natural lengths of the two tether segments respectively. The suffix ϵ reminds that these length variations are for controlling the transverse oscillations.

3.3.3. Libration Damper

Damping of libration is also accomplished by tether length control. As demonstrated in reference [6] the control of librations for a multi-mass tethered system does not differ substantially from the libration control of a two-body tethered system. The only difference being that in an n -mass tethered system, $n-1$ tether lengths must be

controlled; each one with the same control gain. Typical libration control law such as yo-yo or "feed-back" control laws can be adopted. We favor a length control law (or alternatively a rate control law) which uses the in-plane libration angle as a feed-back variable [7]. This control law is effective and easy to implement once the in-plane libration angle is known. In terms of variations of natural tether lengths the libration control law is as follows:

$$\frac{\Delta l_i}{l_{oi}} = -k_\theta \theta \quad i = 1, 2$$

where the suffix θ reminds that the length variations are for controlling the in-plane libration.

If the above equations are added to the equations in section 3.3.2 we obtain the control laws to be implemented into the tether reel and crawler for controlling the in-plane components of transverse oscillations and librations.

3.4 Dynamic Response During Transfer Maneuvers

We ran dynamics simulations in order to explore the dynamic response of the VGL system during its motion from one acceleration level to another. The elevator's transfer maneuvers were divided into three different categories: short-range, medium-range, and large-range. In this section only one simulation is presented for each type of maneuver. The longitudinal dampers are not adaptive while the VGL moves along the tether. The full spectrum of transfer maneuvers are presented in the Progress Reports.

3.4.1 Short Range Maneuvers

In this section we analyze the dynamic response of "short-range" maneuvers of the elevator. Namely we run a simulation with the VGL travelling from 141 m to 154 m (0 g to 5×10^{-6} g). The longitudinal dampers are tuned to the frequencies of the associated tether segments for the elevator at the orbital center (0 g level). Since the

travelled lengths are short the libration and lateral oscillation dampers are inactive. The time constant of the MIMCL control law is $1/\alpha = 500$ s.

The dynamic response of the system is shown in Figures 3.4(a)-3.4(e). In all the above cases the amplitudes of the libration angles are small enough not to require a libration damper. The same comment holds for the lateral in-plane deflection of the elevator with respect to the end-platforms. Namely a transverse oscillation damper is not required for short-range transfer maneuvers.

The station is not significantly perturbed. The maximum value of the longitudinal component of the acceleration on board the elevator during the transfer from one level to another is higher than the final acceleration level. This is not a problem, however, because microgravity experiments, according to this particular scenario, are not carried out during the transfer. Moreover, the acceleration level quickly reaches its steady-state value at the end of the transfer maneuver. A lower acceleration level during a transfer maneuver can be easily attained by increasing the time constant. Consequently the transfer maneuver will be slower.

The side component of the acceleration is negligible. The increase of the front acceleration component leads us to conclude that for longer-range transfer maneuvers the transverse oscillation damper should be activated. Note that the dampers are tuned to the longitudinal frequencies of the tether segments with the elevator at the orbital center. This implies that for these short-range transfer maneuvers the detuning of the longitudinal dampers is moderate and their effectiveness is not impaired.

As a general comment we can say that for this set of short-range transfer maneuvers only the longitudinal dampers need to be activated as long as the time constant of the elevator's control law is greater or equal than 500 s.

3.4.2 Lateral Oscillations of Variable Gravity Laboratory

Before describing the other crawling maneuvers, we would like to address the issue of the build-up of lateral oscillations. Lateral oscillations are a major source of the g-level degradation on board the VGL.

Let us consider a mass M suspended between fixed ends at distances equal to l_2 and $L-l_2$, where L is the total length of the tether, and acted upon two tensions T_1 and T_2 . The equation of motion of the transverse vibration ϵ of the mass M , neglecting the tether mass is:

$$\ddot{\epsilon} + \frac{1}{M} \left(\frac{T_1}{l_2} + \frac{T_2}{L-l_2} \right) \epsilon = 0$$

If we assume that $M = 2000$ kg, $L = 10500$ m, l_2 varies according to the values shown in Table 1, and the tensions are equal to the steady-state values, we can obtain the frequency range of the lateral oscillations during the crawling maneuvers of the Elevator from the above equation. The results are shown in Figure 3.5(a). Since the lateral acceleration a_ϵ is proportional to the square of the frequency f and to the amplitude ϵ , $a_\epsilon = \epsilon(2\pi f)^2$. The g-levels vs frequency are shown in Figure 3.5(b) for a 1-m-amplitude oscillation.

This analysis, though simplified, provides very interesting information on the VGL dynamics. For instance, if a control of the lateral dynamics is introduced with ϵ as a feed-back variable, care must be taken in sensing ϵ with high enough accuracy in order to achieve a specified acceleration noise level. Figure 3.5(c) shows the acceleration noise level versus the frequencies of the lateral oscillations for different accuracies in the computation of the lateral displacement ϵ .

A conclusion can be already drawn: a lateral damper must be introduced in the VGL system in order to damp out the oscillations excited during medium and long range crawling maneuvers.

3.4.3 Medium Range Maneuvers

A numerical simulation was run with the Elevator travelling from 1404 m to 2667 m [Figures 3.6(a)-3.6(g)]. The steady-state acceleration level varies from 5×10^{-4} g to 10^{-3} g.

The Mirror Image Motion Control Law (MIMCL), previously described, was adopted for the crawling maneuver. The simulation was run with the following values of control parameters

$$\gamma = 5 \qquad 1/\alpha = 1000 \text{ sec} \qquad Y = 66.4\%$$

The maneuver takes approximately 1.17 hrs to complete. The maximum crawling-induced-acceleration is 1×10^{-4} g. The in-plane lateral displacement keeps increasing during the maneuver, while the in-plane libration angle is still not significantly perturbed. The out-of-plane lateral displacement of the Elevator and the out-of-plane libration increase more moderately than the in-plane components. The following comments can be made:

- 1) the front acceleration component on board the elevator is influenced by lateral oscillations and it varies according to the formula $\epsilon(2\pi f)^2$.
- 2) The longitudinal component on board the station, because of the lack of a compensatory mass, grows as the elevator's distance from the station increases (see Table 1);
- 3) the detuning of the longitudinal dampers does not affect significantly the acceleration levels on board the elevator and the space station.

3.4.4 Long Range Maneuvers

A numerical simulation was run with the VGL travelling from 2667 m to 10242 m (10^{-3} g to 4×10^{-3} g). The results are shown in Figures 3.7(a)-3.7(g). All the features of the dynamic response pointed out for medium range maneuvers are dramatically magnified in "long range"

crawling maneuvers. The simulation was run with the following control parameters

$$\gamma = 5 \qquad 1/\alpha = 2600 \qquad Y = 66.4\%$$

The maneuver takes approximately 3 hrs to complete. This time the choice of the time constant α is based upon the Elevator's maximum velocity of 1 m/sec.

From Figures 3.7(b) and 3.7(c) it is evident that a libration damper is necessary since the system inertia is no longer able to stabilize the system and in-plane oscillations are the major source of acceleration noise. The front component of the acceleration on board the Elevator and, to a lesser extent, on board the Station are strongly perturbed. Furthermore the front component on board the Elevator, without a libration damper, is not low enough for carrying out useful microgravity experiments.

3.4.5 Crawling Maneuver with Lateral/Libration Damper Activated

With reference to section 3.3 the librational/lateral damper algorithms control the tethers' lengths according to the formulae:

$$l_{c1} = l_{01}(1 - k_{\theta}\theta - k_{\epsilon}\epsilon/l_{01})$$

$$l_{c2} = l_{01}(1 - k_{\theta}\theta + k_{\epsilon}\epsilon/l_{02})$$

The choice of the gains k_{θ} and k_{ϵ} is dictated by the necessity of abating the transient phase very quickly without overloading the performance of the tethers' reels. For this simulation run we set the control gains to $k_{\theta} = k_{\epsilon} = 1$.

The system dynamic response is shown in Figure 3.8(a)-3.8(g). These plots must be compared to the corresponding plots of Figures 3.7. The controlled length is slightly different from the previous run because of the amount of tether reeled in and out to control the in-plane dynamics. The in-plane angle θ and the VGL in-plane deflection are efficiently damped out. Once the desired amplitudes are attained, the in-plane libration and lateral dampers can be switched off without

impairing the system performance. The out-of-plane dynamics is unaffected.

The front component of the acceleration on board the Station, is reduced to 12%. The Elevator, however, benefits the most by the active control of the in-plane dynamics. From the plots it is also evident that the harmonic components of the acceleration at the frequency of the lateral oscillations have been completely abated in both front and longitudinal acceleration components.

3.4.6 Fast Crawling Maneuvers (FCM)

Maneuvers with time constants shorter than those previously considered have been analyzed.

Even though shortening the crawling times is surely cost effective there are concerns from the dynamical point of view, namely:

- 1) strong perturbations can be excited and are difficult to abate or have long relaxation times that defeat the goal of having the Elevator readily available at the end of the crawling. In other words, the time saved in transferring the Elevator is lost in damping the transient phases;
- 2) a libration/lateral damper must be adopted, but depending on the reel characteristics, severe constraints can be posed on its design such as high control velocities.

To this end the maximum crawling velocity of the Elevator is assumed to be equal to 1 m/sec. Furthermore the travelled distances of possible FCM have been restricted between hundreds of meters and a few Kilometers because in the low-g range the system is very sensitive to distances of a few meters. As shown in Table 1 the acceleration level varies from 0 g to 10^{-5} g over approximately 26 meters, so that a very fine g-tuning is required and this might not be achievable with a fast maneuver. On the other end, it was shown that the time constant for transfer maneuvers of several kilometers was

limited by the maximum velocity of the Elevator and therefore the "Long Range" maneuvers can be already considered FCM's.

Hence the feasibility analysis for FCM's is relevant to maneuvers from 10^{-5} g to 10^{-3} g.

For the sake of brevity only one FCM is presented in this section, namely the maneuver from 1404 m off the Space Station to 2667 m. FCM maneuvers, not shown here, have a behavior similar to the one described in the following. The libration/lateral dampers are activated throughout the whole simulation. In principle, these dampers could be switched off after the transient phase has been abated since the environmental forces are unable by themselves to significantly perturb the system. On the contrary the longitudinal dampers must be always activated when microgravity activities are conducted.

Figures 3.9(a)-3.9(e) show the dynamic response of FCM simulation. The time constant α has been reduced to $1/500 \text{ sec}^{-1}$. The transfer time is reduced from 1.17 hrs to 35 min. The maximum crawling velocity is 0.9 m/sec. The control gains adopted are:

$$K_{\theta} = K_{\epsilon} = 1$$

Figure 3.9(a) shows the tether length while, Figures 3.9(b) and 3.9(c) show the damping terms $k_{\theta}\theta$ and $k_{\epsilon}\epsilon$, respectively. The reel performance required is well within the current capabilities of tethers' reels. Figure 3.9(d) shows the front and lateral component of the acceleration acting on board the VGL. The longitudinal component is shown in Figure 3.9(e). The transient phase is quite short. The longitudinal component has the same damping characteristics of the front component (damping ratio = 17%).

3.5 Spectral Analysis of Acceleration Levels on Board VGL

The study performed so far has shown the effects of some of the main environmental perturbations upon the VGL acceleration's levels. Nevertheless it seems necessary at this point to focus the attention on the general perturbations that affect the "quality" of the g-levels on

board the VGL. Schematically these perturbations can be divided in four main categories:

- 1) Orbital perturbations (J_2 , atmospheric drag, attitude motions)
- 2) Tether-related perturbations (librations, longitudinal oscillations, lateral oscillations)
- 3) VGL-perturbations (structural, man-made, outgassing)
- 4) Space Station-perturbations (all disturbances coming from the station and transmitted through the tether)

An harmonic analysis of the accelerations acting on board VGL was performed. Even though Fourier analysis is useful in finding the frequencies at which the perturbations act, care must be taken in analyzing the spectral magnitudes. These, in fact, are strictly related to the initial conditions and above all to the damping acting on a particular mode. Hence the spectral analysis should be used primarily to identify the frequency content of a given signal.

To this end the station-keeping phase of a FCM, when $l_2=2667$ m, has been compared to the same phase of the standard simulation (Figures 3.6). The main difference being that in the FCM the libration/lateral dampers are activated while in the other simulation the lateral mode is strongly excited because the dampers are off. Both systems are modelled by three lumps so that the vibration modes of the tethers can not be seen.

The natural frequencies of the equivalent 2-mass/2-spring system are as follows

3.12×10^{-2} Hz	I "Spring-mass" mode
1.15×10^{-1} Hz	II "Spring-mass" mode
9.12×10^{-4} Hz	Lateral vibration mode

Figures 3.10(a)-3.10(d) show the spectra of the front and longitudinal component of the acceleration acting on board the VGL. The action of the libration/lateral dampers is quite evident when the spectra of the front components are compared [Figure 3.10(a) and 3.10(b)]. The effects of the accelerations due to the lateral oscillations are the most significant. The amplitude of the lateral mode has been reduced by three orders of magnitude by the damper. No peaks are present for frequencies larger than 5×10^{-3} Hz because the tether oscillatory modes are not modelled.

The longitudinal components show in both cases [Figure 3.10(c) and 3.10(d)] two separate groups of frequencies. The lower frequency ($< 5 \times 10^{-3}$ Hz) is related to the orbital dynamics (first peak) and lateral oscillations (second peak), while the frequency group between 2×10^{-2} and 1.2×10^{-1} Hz is related to the tether longitudinal dynamics. No other peaks are present for frequencies larger than 1.4×10^{-1} Hz because the tether oscillatory modes are not modelled in this simulation run. Notice that the peaks at higher frequencies present some "leakage" phenomena. This phenomena could be reduced by "Hanning" the data, which would cause however, a reduction of the harmonic amplitudes. Also for the longitudinal oscillations the effect of the libration/lateral dampers is evident.

3.6 Disturbance Propagation Along Tethers

Oscillations of the tether attachment point to the station generate waves which propagate along the tether to the elevator and beyond to the end platform. Since the station is a source of non-negligible dynamic noise the impact of the station-related disturbances on the elevator acceleration level may be more important than the effect of the environmental perturbations. The station accounts for oscillations with a wide range of frequencies. In particular, the low frequency (around 10^{-3} Hz) disturbances are associated with aerodynamic and orbital perturbations; the medium frequency (from 10^{-2} Hz to 10 Hz) disturbances with the structural vibrations of the station; and the high frequency (> 10 Hz)

disturbances with rotating machinery and human activity on board the station.

The wave propagation is affected by the tether characteristics of mass, stiffness, and material damping, by the tensions in the two tether segments, and by the geometry of the system. The impact of the longitudinal waves upon the elevator acceleration level also varies depending on the presence or absence of longitudinal dampers at the tether attachment points.

The following analysis is based on an analytical solution to the wave equations in a two-tether-segment system (like the VGL) derived in reference [8]. This model is based on the assumptions of small oscillations, viscous material damping, tether as a perfectly elastic continuum, and unconstrained elevator and end platform. The equations of motion in non-dimensional form are given by [8]:

$$\begin{aligned}
 u_{jtt} &= \epsilon_j^2 \left(1 + b \frac{\partial}{\partial t}\right) u_{jz_j} + \gamma u_j & j &= 1, 2 \\
 u_{2tt} &= -\epsilon_2^2 a_2 \lambda_2 \left(1 + b \frac{\partial}{\partial t}\right) u_{2z_2} + \gamma u_2 & z_2 &= 1 \\
 u_{1tt} &= -\epsilon_1^2 a_1 \lambda_1 \left(1 + b \frac{\partial}{\partial t}\right) u_{1z_1} - \epsilon_2^2 a_1 \lambda_2 \left(1 + b \frac{\partial}{\partial t}\right) u_{2z_2} + \gamma u_1 & (16) \\
 & & z_1 &= 1; z_2 = 0 \\
 u_2(0, t) &= u_1(1, t) \\
 u_1 &= e^{i\omega t} & z_1 &= 0
 \end{aligned}$$

The subscripts t and z_j indicate partial derivatives with respect to time and vertical coordinates respectively. The dimensionless vertical coordinates for tether segments 1 and 2 are $z_1 = z_1/L_1$ and $z_2 = z_2/L_2$ where z_1 and z_2 are the dimensional quantities. Likewise u_1 and u_2 are

the dimensionless longitudinal tether stretches while $t = \underline{t}\Omega$ is the dimensionless time. μ is the tether linear density, Ω the orbital rate, m_1 and m_2 the masses of the elevator and the upper-platform respectively, EA the tether stiffness, $E'A$ the tether axial viscosity, and ω the angular frequency of the perturbation. The dimensionless coefficients in eqt. (1) are as follows: $\varepsilon_1 = c/\Omega L_1$, $\varepsilon_2 = c/\Omega L_2$, $a_1 = L\mu/m_1$, $a_2 = L\mu/m_2$, $\lambda_1 = L_1/L$, $\lambda_2 = L_2/L = 1 - \lambda_1$, $b = E'A\Omega/EA$ and $\gamma = 3$, where $c = (EA/\mu)^{1/2}$ is the longitudinal wave speed, L_1 and L_2 are the lengths of the two tether segments, while L is the overall length of the tether.

As indicated in reference [9] the tether damping is best approximated by a combination of viscous and structural damping. The purely viscous model, however, leads to an analytic solution of the equation and provides results which are accurate enough in the neighborhood of a specific frequency. Once the actual damping value is known for a certain frequency (not yet the case for long braided tethers in space) the equivalent viscous damping value for that frequency can be adopted to interpret the results. The viscous damping model provides results which are conservative for frequencies lower than the equivalent-damping-frequency and non-conservative for higher frequencies.

The longitudinal acceleration at the elevator for a unit sinusoidal longitudinal acceleration at the tether/station attachment point, that is the Frequency Response Function (FRF), is given by:

$$R_1(1) = [\cos\beta_1 - \delta_1 \sin\beta_1 - \frac{\sin\beta_1 \sin\beta_2 + \delta_2 \sin\beta_1 \cos\beta_2}{\cos\beta_2 - \delta_2 \sin\beta_2}]^{-1} \quad (17)$$

where

$$\beta = \sqrt{\frac{\omega^2 + \gamma}{1 + i\omega b}}$$

$$\beta_1 = \beta/\varepsilon_1$$

$$\beta_2 = \beta/\varepsilon_2 \tag{18}$$

$$\delta_1 = \beta_1/(a_1\lambda_1)$$

$$\delta_2 = \beta_2/(a_2\lambda_2)$$

Figures 3.11(a), 3.11(b), and 3.11(c) show the magnitude of the longitudinal wave FRF at the elevator for a fractional distance between elevator and station $\lambda_1 = 0.1, 0.5$, and 0.9 respectively. The material damping is assumed equal to zero and the plots clearly show the longitudinal resonance frequencies for the three different position of the elevator along the tether. The resonance spikes for these undamped cases are of course infinite and are limited in the plots only as a result of the sampled plotting step. In Figure 3.11(a) the two lowest frequencies of 0.04 Hz and 0.14 Hz are the two spring-mass longitudinal modes of the system. The other spikes correspond to the harmonics of the longitudinal modes of tether segment 2 (between the elevator and the end platform) while the spike at 1.76 Hz is the first longitudinal harmonic of tether segment 1. In Fig. 3.11(b) the two lowest frequencies of 0.036 Hz and 0.097 Hz are the spring-mass modes of the system. The remaining spikes are the longitudinal harmonics of tether segments 1 and 2 which are paired together. In Fig. 3.11(c) the two spring-mass modes have frequencies of 0.04 Hz and 0.19 Hz. The remaining spikes are the harmonics of the longitudinal modes of tether segment 1 while the spike at 1.76 Hz is the first longitudinal mode of tether segment 2.

If we now assume a 2% damping ratio for the first longitudinal tether mode, as adopted in the numerical simulation runs, the resonance spikes are attenuated and finite as shown in Figs. 3.12(a), 3.12(b), and 3.12(c). We must point out, however, that low frequency disturbances (< 0.2 Hz) propagate with no attenuation. The small

material damping has a very limited effect on the spring-mass modes of the system. Furthermore, these modes have frequencies close to the first bending mode of the station which is equal to 0.1 Hz for the 3-m-truss station and to 0.2 Hz for the 5-m-truss station. The amplitudes of the spring-mass modes can be reduced by adding tuned longitudinal dampers (as already accounted for in the numerical model) which are not included in this analytical model. However, the frequencies of the spring-mass modes, around 0.1 Hz, are still far too high to provide a satisfactory attenuation of the first structural mode of the station which is also around 0.1 Hz.

The high frequencies of the spring-mass modes are a result of the tether stiffness characteristics. Stiff tethers transmit disturbances better than soft tethers. This analysis of the wave propagation emphasizes the need for a softer tether and eventually for assessing the minimum value of the tether diameter which provides the desired life expectancy.

3.7 Attitude Dynamics of Variable Gravity Laboratory

It is well known that the rotational motion will be one of the major sources of noise upon the accelerations acting on board the Space Station, and as it will be shown in the following, the same happens for the VGL. The rotational effects, however, are somewhat mitigated in the VGL because of the reduced dimensions and distribution of mass.

3.7.1 Mathematical Model

In SAO's MASTER20 code the attitude motion of the Elevator is described with respect to a body reference frame with the origin located in the platform's center of mass and the axis x_1 , x_2 , x_3 oriented along the three principal axes (Figure 3.13).

A 3-1-3 rotation sequence has been chosen to define the three Euler's angles with respect to the inertial reference frame [10]. The three Euler's equations can be written as [11]

$$\begin{aligned}
I_1 \dot{\omega}_1 + (I_3 - I_2) \omega_2 \omega_3 - H_1 &= 0 \\
I_2 \dot{\omega}_2 + (I_1 - I_3) \omega_1 \omega_3 - H_2 &= 0 \\
I_3 \dot{\omega}_3 + (I_2 - I_1) \omega_1 \omega_2 - H_3 &= 0
\end{aligned} \tag{19}$$

where I_1 , I_2 , and I_3 are the moments of inertia around the principal axes x_1 , x_2 , and x_3 respectively, ω_1 , ω_2 , ω_3 are the component of the angular velocity $\underline{\Omega}$, and H_1 , H_2 , and H_3 are the components of the external torque applied to the VGL. Equations (1) are numerically integrated with the three kinematics equations that relate $\underline{\Omega}$, to the Euler angle rate $\dot{\alpha}$ as follows [11]

$$\dot{\alpha} = \frac{1}{s\alpha_2} \begin{vmatrix} s\alpha_3 & c\alpha_3 & 0 \\ c\alpha_3 s\alpha_2 & -s\alpha_3 s\alpha_2 & 0 \\ -s\alpha_3 c\alpha_2 & -c\alpha_3 c\alpha_2 & s\alpha_2 \end{vmatrix} \underline{\Omega}$$

where s stands for $\sin()$ and c stands for $\cos()$.

A better description of VGL's rotational motion is given by erecting a reference frame x_A , y_A , z_A with the origin located at the VGL's center of mass and axes defined as [10]

- x_A - axis along the VGL velocity component in the orbital plane
- z_A - axis along the local vertical toward the Earth
- y_A - axis completes the right-handed reference frame

It is well known that the three rotational displacements of the body reference frame from the x_A , y_A , z_A frame are the yaw angle ψ the pitch angle β and the roll angle γ (3-2-1 rotation sequence).

The external torques are computed by taking only the contributions of the tether tensions into account (elastic and viscous terms). MASTER20, however, can handle also the gravity gradient torques and

the aerodynamic torques provided that for the latter the coordinates of the center of pressure are given as a input.

3.7.2 Attitude Motion of VGL

The preliminary VGL geometrical configuration chosen by Aeritalia for the 2000 kg-Elevator is

1.7 m	in-plane flight direction
1.3 m	vertical direction
1.2 m	out-of-plane flight direction

The principal moments of inertia are

$$I_1 = 608 \text{ kg-m}^2$$

$$I_2 = 763 \text{ kg-m}^2$$

$$I_3 = 808 \text{ kg-m}^2$$

The equations which describe the attitude dynamics of the VGL orbiting the Earth at constant rate Ω under the assumption of small angles, are [12]:

$$\begin{aligned}
 \text{roll)} \quad & \ddot{\gamma} + a \Omega^2 \gamma - (1-a)\Omega\dot{\psi} = -(T_1 + T_2) \delta \gamma / I_1 \\
 \text{yaw)} \quad & \ddot{\psi} + b \Omega^2 \psi - (1-b) \Omega \dot{\gamma} = 0 \\
 \text{pitch)} \quad & \ddot{\beta} + c \Omega^2 \beta = -(T_1 + T_2) \delta \beta / I_2
 \end{aligned} \tag{20}$$

where

$$a = (I_2 - I_3) / I_1$$

$$b = (I_2 - I_1) / I_3$$

$$c = (I_1 - I_3) / I_2$$

$$T_1 = \text{lower tether tension}$$

- T_2 = upper tether tension
 δ = distance between VGL's center of mass and
 tethers' attachment points

Under the above mentioned hypotheses the pitch dynamics is decoupled by yaw and roll dynamics. On the other hand the yaw and roll dynamics are coupled. Each mode is excited by the other's rate, but this influence is attenuated by the factors (1-a) for the roll and (1-b) for the yaw. In our case, (1-a) and (1-b) are almost equal to unity.

Equations (2) can assume a more compact form if one notes that for our purposes

$$(T_1 + T_2)\delta / I_1 \gg a \Omega^2$$

$$(T_1 + T_2)\delta / I_2 \gg c \Omega^2$$

so that

$$\text{roll)} \quad \ddot{\gamma} + \frac{k}{I_1} \gamma = (1-a) \Omega \dot{\psi}$$

$$\text{yaw)} \quad \ddot{\psi} + b \Omega^2 \psi = (1-b) \Omega \dot{\gamma}$$

$$\text{pitch)} \quad \ddot{\beta} + \frac{k}{I_2} \beta = 0$$

where $k = (T_1 + T_2)\delta$

The pitch natural frequency f_p is

$$f_p = \frac{1}{2\pi} \sqrt{\frac{k}{I_2}}$$

Figure 3.14 shows the pitch frequency for our system and the lateral and longitudinal frequencies versus the distance of the VGL from the Space Station. The pitch frequency is comprised between the two spring-mass modal frequencies and ranges from 7.1×10^{-2} Hz with VGL at the orbital center to 8.2×10^{-2} with VGL at 10242 m off the

Space Station (4×10^{-3} g location). No resonance appears, even though the tethers' higher modes (longitudinal and lateral) are not included.

3.7.3 Rotational Acceleration Noise on Board VGL

The acceleration measured by an accelerometer package in a point P shifted from the VGL's Center of Mass with the sensors aligned with the body axes can be expressed as

$$\underline{A}_P = - [\underline{A}_{CM} + \underline{\Omega} \times \underline{r}_P + \underline{\Omega} \times (\underline{\Omega} \times \underline{r}_P)] \quad (21)$$

where

\underline{r}_P = position vector of P with respect to the body reference frame

$\underline{\Omega}$ = angular rate of the body reference frame

\underline{A}_{CM} = acceleration at the VGL's Center of Mass

The minus sign indicates that the acceleration A_p is apparent and therefore opposed to the inertial. The $-$ sign is due to the fact that the gravity gradient acceleration related to the shift between the CM and the attachment point (at most equal to 2.5×10^{-7} g) has been neglected.

From the right-hand side of equation (4) it is evident how the tangential (2nd) and the centrifugal terms (3rd) can limit the volume where the low-gravity experiments are carried out. In fact, even though the geometrical dimensions of the VGL are small, large angular rates or their derivatives can reduce the space available for experiments. All this however has to be assessed quantitatively in order to provide adequate damping techniques.

3.7.4. Numerical Simulations

Numerical simulations have been run to show how the attitude motion affects the acceleration field on board VGL, namely:

- A) Station keeping with VGL at 2667 m off the Space Station
- B) VGL crawling from 2667 m to 10242 m off the Space Station
- C) Same as B) but with the in-plane libration/lateral dampers activated

3.7.4.1 VGL Dynamics Response for Station-Keeping

Figures 3.15(a)-3.15(g) show the dynamic response of run (A). Comparing the in-plane angle θ and out-of-plane angle ϕ [Figure 3.15(a)] with the pitch and roll angles respectively [Figure 3.15(b) and 3.15(c)], we note that they have similar behavior. The low-frequency librations of the system are driving the whole dynamics. A higher frequency component, however, is superimposed on the pitch and roll modes due to their natural frequencies. The yaw angle shown in Figure 3.15(d) is influenced by the roll rate according to equations (20), but the amplitude of oscillation is smaller than the roll's. Figures 3.15(e), 3.15(f), and 3.15(g) show the acceleration components acting on VGL's center of mass along the body axes. The influence of the VGL rotation is particularly evident for the component acting along axis 1. Note, however, that this is not what we refer as "rotational noise" [see Equation (21)] but simply a modulation of the accelerations acting on VGL's CM at the attitude's natural frequencies.

In order to clarify this concept the data of run (A) have been post-processed using equations (21) to compute the accelerations acting upon other points within VGL's volume, namely

$P = P(0.85, 0, 0)$ the farthest point on axis 1 (flight direction)

and

$Q = Q(0, 0, 0.65)$ the lowest point on axis 3 (toward earth)

The spectra of the acceleration components are shown in Figures 3.16(a)-3.16(f). Note that the dc component has been subtracted and only the accelerations along axis 1 and 3 have been considered.

With reference to Figure 3.14, the system's natural frequencies when VGL is at 2667 m off the Station are

I "Spring-mass" mode	1.15×10^{-1} Hz
II "Spring-mass" mode	3.12×10^{-2} Hz
"String-like" mode	9.11×10^{-4} Hz
Pitch mode	7.36×10^{-2} Hz

Due to the complexity of the coupling among the three rotational DOF's it is hard to separate the effects of different contributions on the accelerations components. Nevertheless, the accelerations components along axis 1 seem to be influenced mainly by the "string-like" mode and the pitch mode. The latter mode, actually, plays a major role in the spectra of the acceleration in Q with a peak amplitude of 1.41×10^{-5} g. The opposite happens to the acceleration components along axis-3. Point P, in fact, is the most affected by the pitch mode with a peak amplitude of 1.78×10^{-5} g. This is caused by the action of the tangential term $[\underline{\Omega} \times \underline{r}]$ of the acceleration. Note also in Figure 3.16(b) a small peak at twice the pitch frequency due to the action of the centrifugal term $[\underline{\Omega} \times (\underline{\Omega} \times \underline{r})]$.

3.7.4.2 VGL Dynamic Response for Crawling Maneuvers

The VLG crawling maneuver from 2667 m to 10242 m off the Space Station has been used as test case to study the attitude dynamics of our system when the Elevator is in motion. Main Purposes for studying this case are:

- 1) To compare the effects of the System's attitude dynamics when the libration/lateral damper is activated or not
- 2) To assess the presence of undesired build-up of attitude oscillations caused by the Elevator's motion.

As it was pointed out in the previous paragraph, the system's librations are superimposed to the roll and pitch angles so that the activation of the libration/lateral dampers to control the attitude dynamics might be helpful. The libration/lateral damper, however, cannot be considered the solution for damping the rotational modes since it operates in a range of frequencies ($\sim 10^{-4}$ Hz) different from the pitch natural frequencies ($\sim 7 \times 10^{-2}$ Hz). Only adequate dampers turned on those frequencies can serve the purpose.

Figures 3.17(a)-3.17(f) show the dynamic response of run (B). At the end of the maneuver the lateral oscillations are the source which mostly affect the pitch angle. The roll and the yaw angles, instead, show the same feature of run (A). Figures 3.17(d), 3.17(e) and 3.17(f) show the acceleration components acting on board VGL along the three body axes respectively. The attitude frequencies are evident for the axis-2 component (high frequencies harmonics). On the contrary, because of the lateral dynamics for axis-1 component and of the final dc value for the axis-3 component, the attitude frequencies are not visible.

Figures 3.18(a)-3.18(f) show the result of run (C). These plots must be compared to the corresponding plots of Figures 3.17. By dissipating the system oscillations (in plane libration and lateral displacement) the dampers decrease the energy transfer to the

rotational DOF's. Consequently, the peak-to-peak amplitude of the pitch angle at the end of the maneuver decreases. The roll and yaw angles remain unchanged. The effect of the energy dissipation appears also in the axis-1 acceleration component where only the high frequency harmonic of the pitch mode are present. In the case of axis-3 the ripples of the lateral displacement have disappeared but, because of the final dc value, the attitude harmonics are still not visible.

3.8 Concluding Remarks

The analysis of the dynamic response of the crawling maneuver has been performed. By adopting the Mirror Image Motion Control Law (MIMCL) relatively efficient transfer maneuvers are obtained. The acceleration level during the transfer is higher than the final acceleration level but the system quickly attains the steady-state final acceleration level. Moreover, for moderate (up to few hundreds meters) values of travelled lengths, only the longitudinal dampers are required.

Although the adequacy of the Mirror Image Control Law (MICL) has been assessed for all types of maneuvers, the adoption of a libration/lateral damper resulted to be necessary for medium/long range maneuvers. The system, in fact, can not damp out the crawling-induced transient phases without such a device.

The algorithm adopted for the libration/lateral damper has been successfully tested. The crawling-induced-accelerations are effectively damped out and the acceleration profiles are suitable for microgravity applications. Furthermore a libration/lateral damper might be useful in speeding up the duration of crawling maneuvers, by abating the Coriolis-induced oscillations and the transient phases at the end of the maneuver. The longitudinal perturbations are effectively abated when the elevator is far away from the orbital center where the longitudinal dampers are tuned.

As confirmed by a harmonic analysis of the VGL accelerations components, the action of the damping devices has proved effective over a wide range of frequencies (10^{-3} - 10^{-1} Hz).

The noise generated by the Space Station and transmitted through the tether to the VGL can be a source of non negligible disturbance unless the tether is soft enough or attenuation devices are inserted between the Station and the tether attachment point.

The analysis of the VGL attitude dynamics has shown that the rotational motion can be source of significant acceleration noise acting upon the laboratory. Severe limits can be posed on the payloads accommodation unless suitable dampers are adopted. The in-plane libration/lateral dampers have shown their effectiveness in limiting the energy transfer from low frequency disturbances but cannot be considered effective attitude dampers since they are not tuned to the attitude frequencies.

3.9 References to Section 3

- [1] Swenson, F.R., G. von Tiesenhausen, "Optimization of Motion Control Laws for Tether Crawler or Elevator Systems," Proceedings of the Second International Conference on Tethers in Space, 4-8 October 1987, Venice, Italy, pp. 605-608.
- [2] Lorenzini, E.C. (PI), "Analytical Investigation of the Dynamics of Tethered Constellations in Earth Orbit (Phase II)," Quarterly Report #10 prepared for NASA/MSFC Contract NAS8-36606, October 1987.
- [3] Lorenzini, E.C., M. Cosmo, S. Vetrella and A. Moccia, "Dynamics and Control of the Tether Elevator/Crawler System," Journal of Guidance, Control, and Dynamics, November/December 1988, Vol. 12, No.3, May-June 1989, pp. 404-411
- [4] Swenson, F.R., "Tether Crawler System," Tri-State University Report for NASA/MSFC, Contract NGT 01-002-099, August 11986.
- [5] Bevilacqua, F., P. Merlina, "The Tethered Space Elevator System," Proceedings of the Second International Conference on Tethers in Space, 4-8 October 1987, Venice, Italy, pp. 365-373.
- [6] Cosmo M., E.C. Lorenzini, S. Vetrella and A. Moccia, "Transient Dynamics of the Tether Elevator/Crawler System," Proceedings of the AIAA/AAS Astrodynamics Conference, August 15-17, 1988, Minneapolis, MN, pp. 480-489.
- [7] Lorenzini E.C., "A Three-Mass Tethered System for Micro-g/Variable-g Applications," Journal of Guidance, Control, and Dynamics, Vol. 10, No.3, May-June 1987, pp. 242-249.
- [8] Lorenzini E.C. and M. Cosmo, "Wave Propagation in the Tether Elevator/Crawler System", to appear in Proceedings of the Tether Dynamics Workshop, 16 May 1989, San Francisco, CA.

- [9] He X. and D. Powell, "Tether Damping in Space", to appear in Journal of Guidance, Navigation and Control, 1989.
- [10] Vetrella, S., A. Moccia, E.C. Lorenzini, and M. Cosmo, "Attitude Dynamics of the Tether Elevator/Crawler System for Micro-Gravity Applications." Proceedings of the 2nd International Conference on Tethers in Space, San Francisco, CA, May 17-19, 1989, pp.323-330.
- [11] Wertz, J.R. (Ed.), "Spacecraft Attitude Determination and Control," D. Reidel Publishing Company, 1978.
- [12] Lemke, L.G., J.D. Powell, and X. He, "Attitude Control of a Tethered Spacecraft." The Journal of the Astronautical Sciences, Vol. 35, January-March, 1987, pp. 41-55.

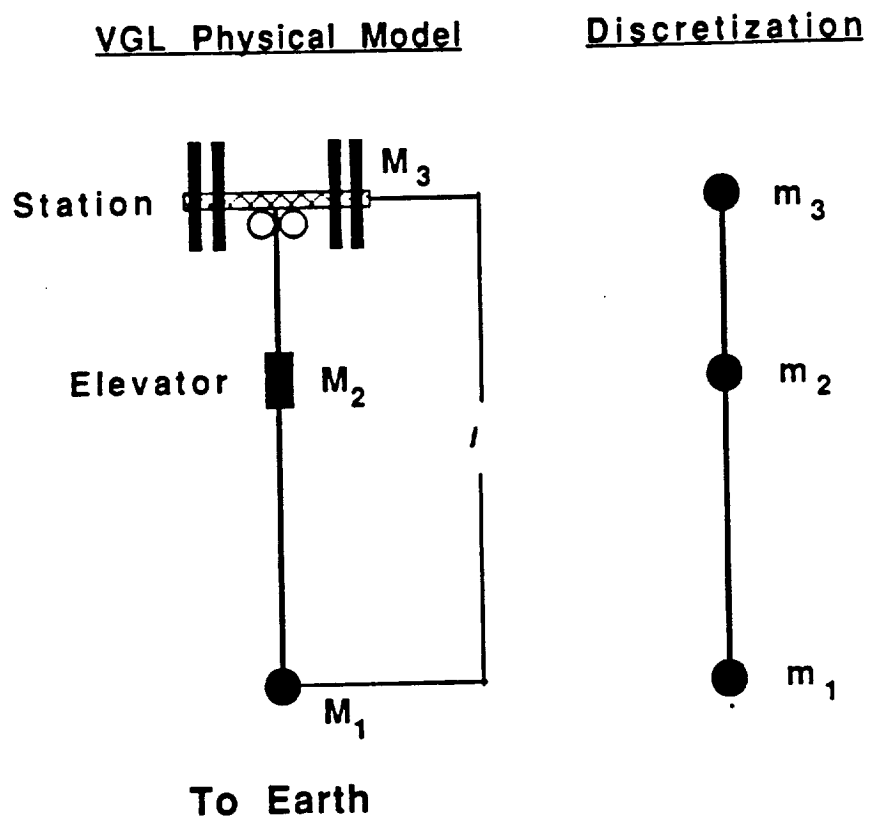


Figure 3.1

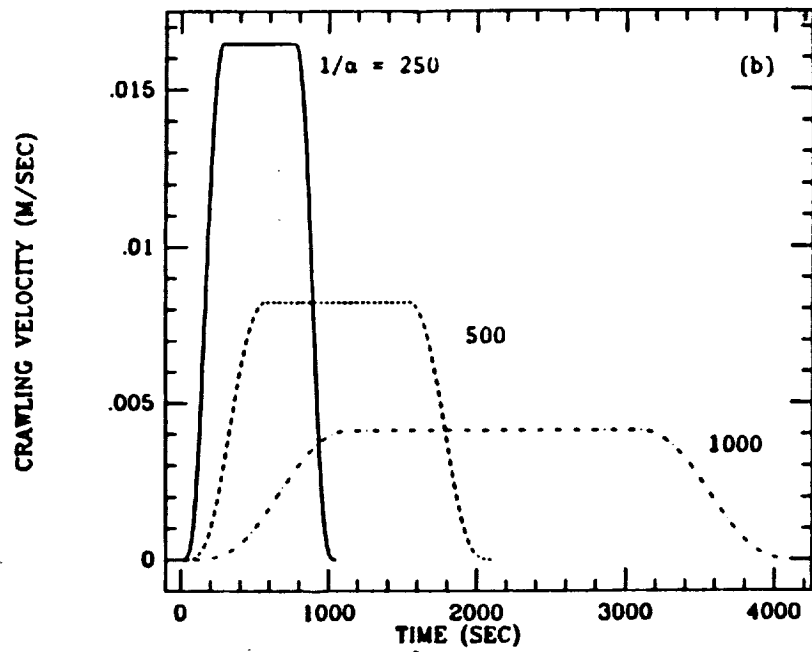
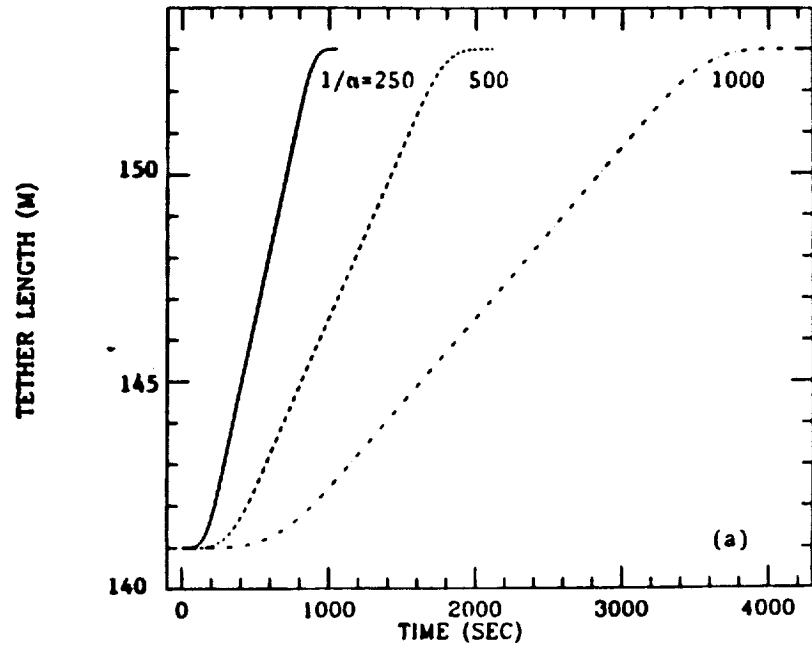
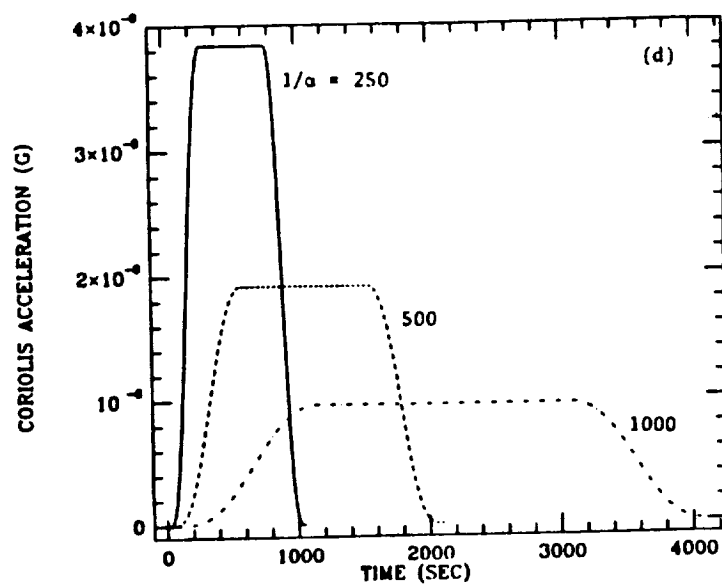
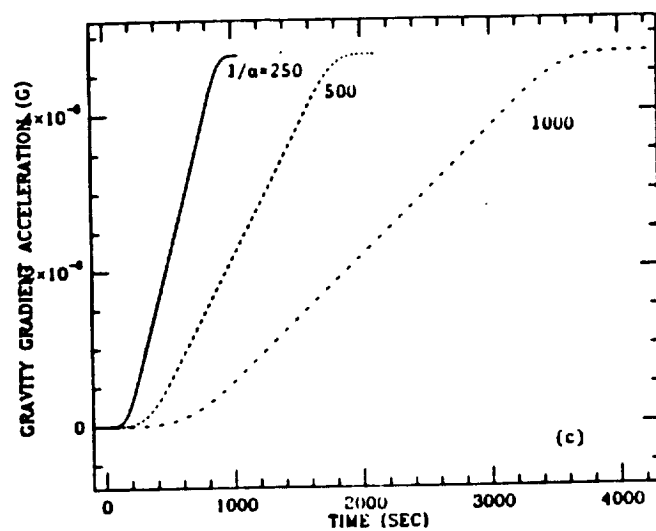
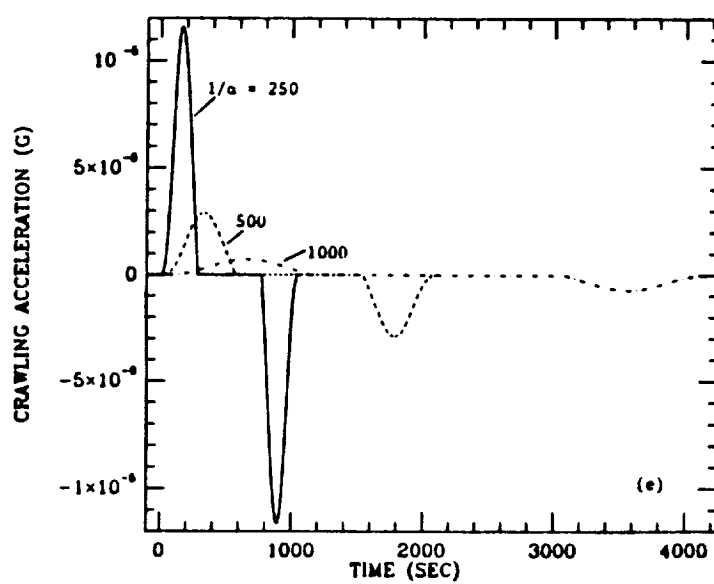
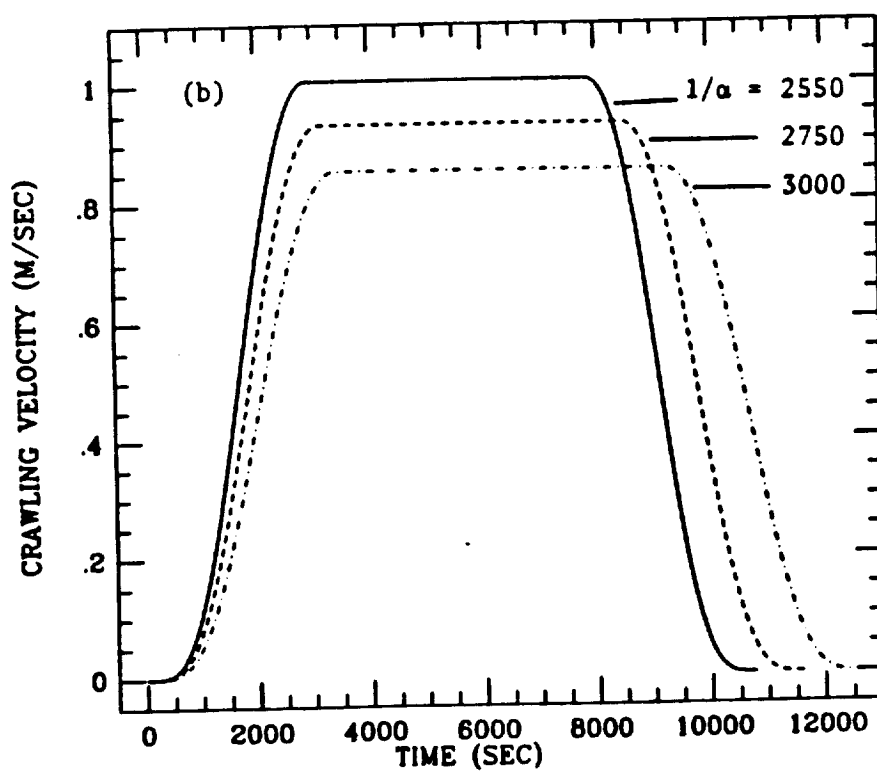
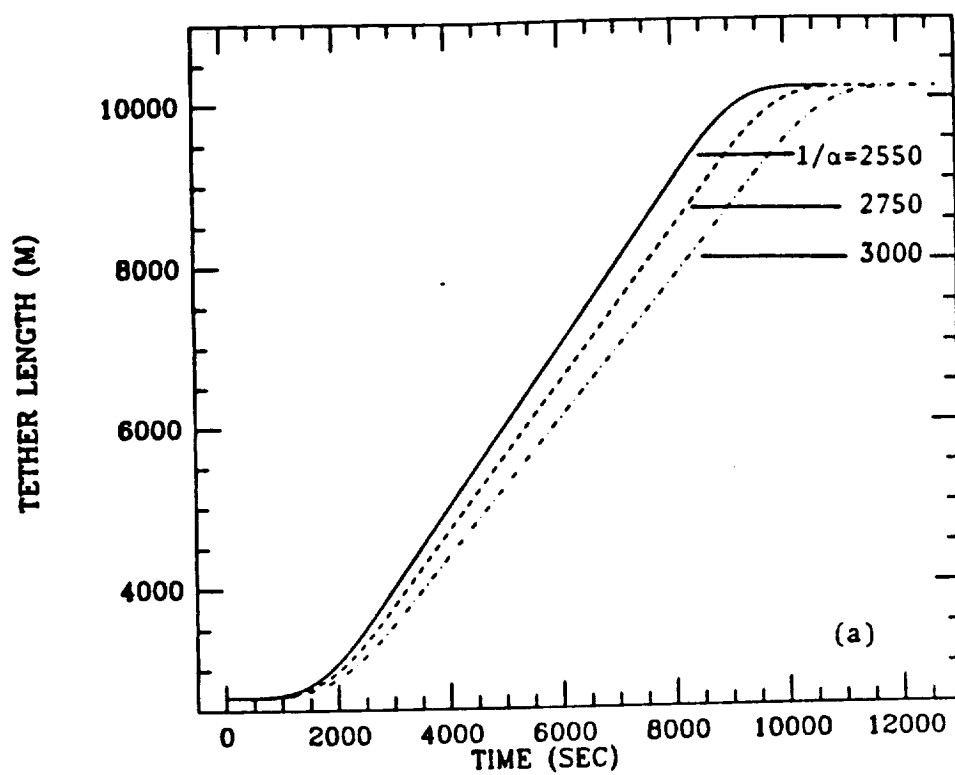


Figure 3.2(a)-(b)

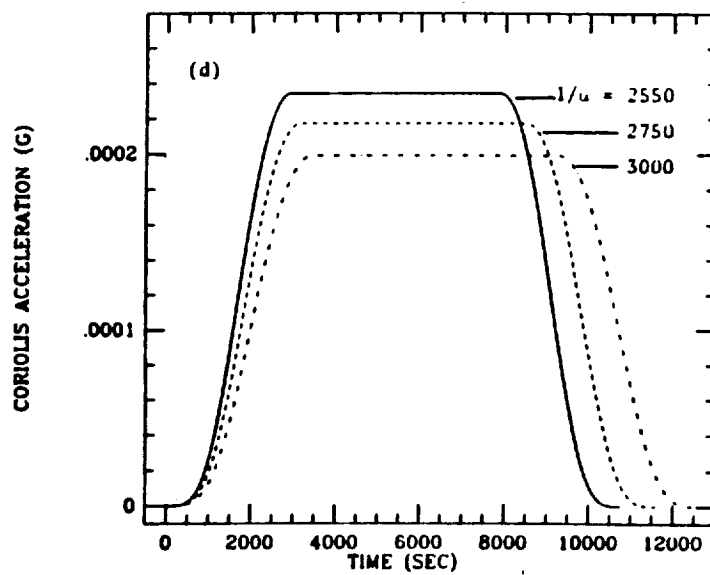
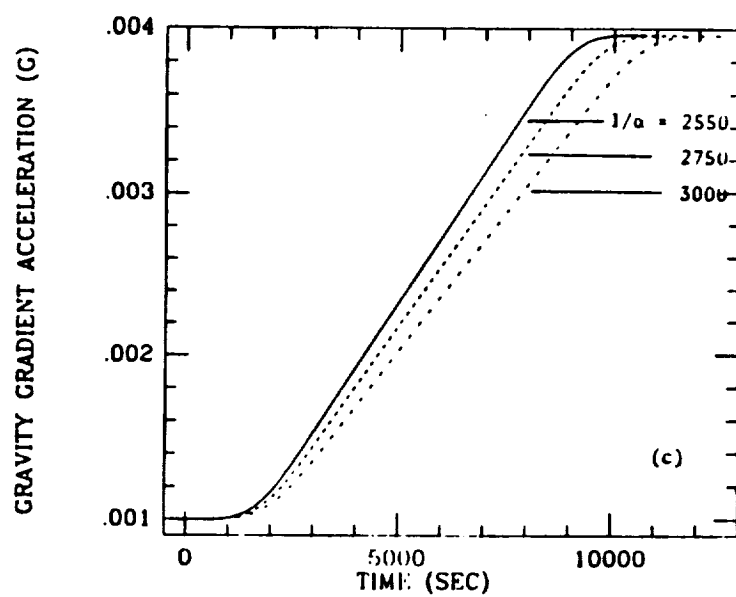


Figures 3.2(c)-(d)

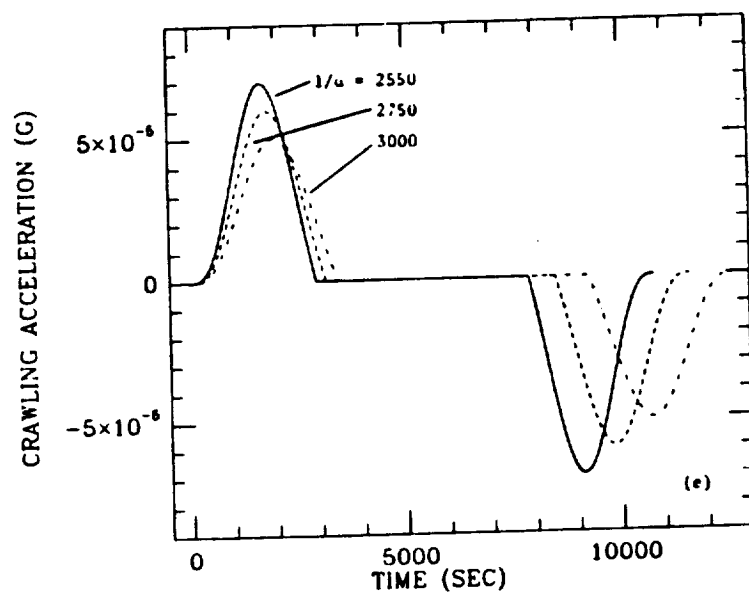
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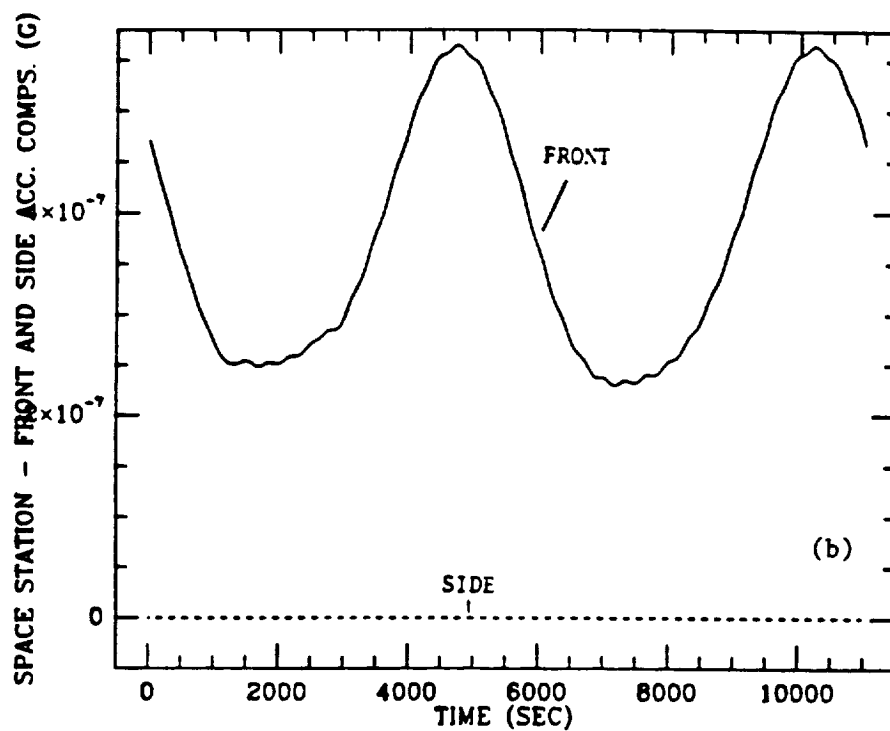
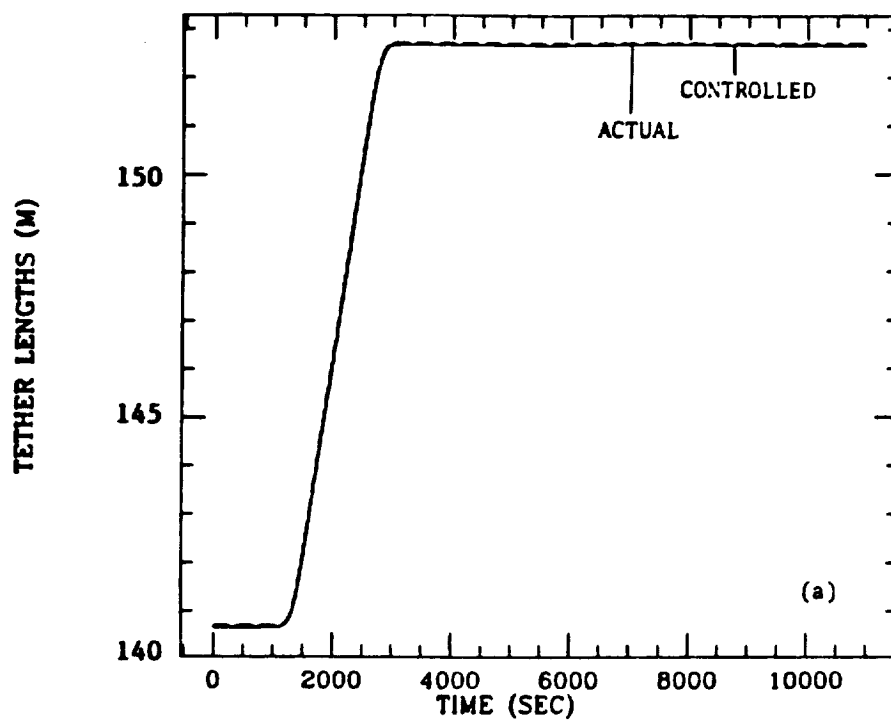


Figures 3.3(a)-(b)

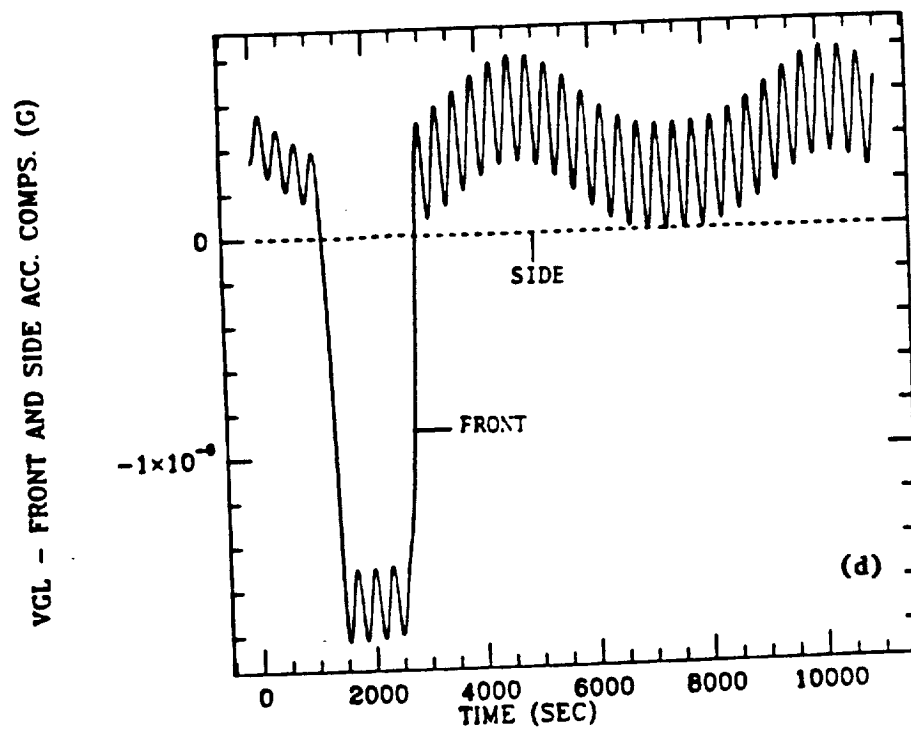
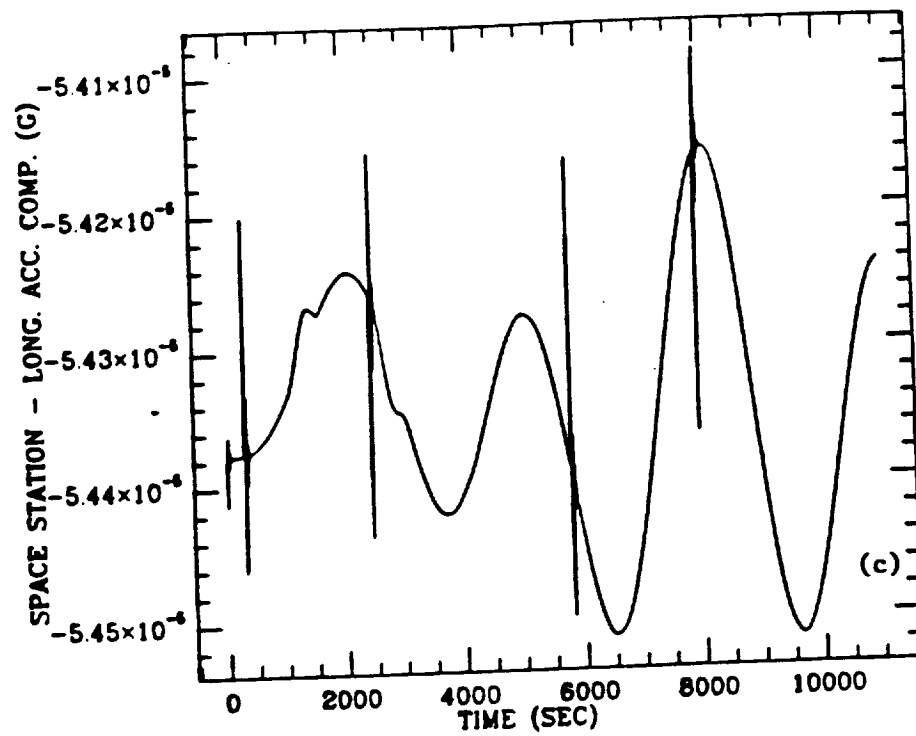


Figures 3.3(c)-(d)

**Figure 3.3(e)**



Figures 3.4(a)-(b)



Figures 3.4(c)-(d)

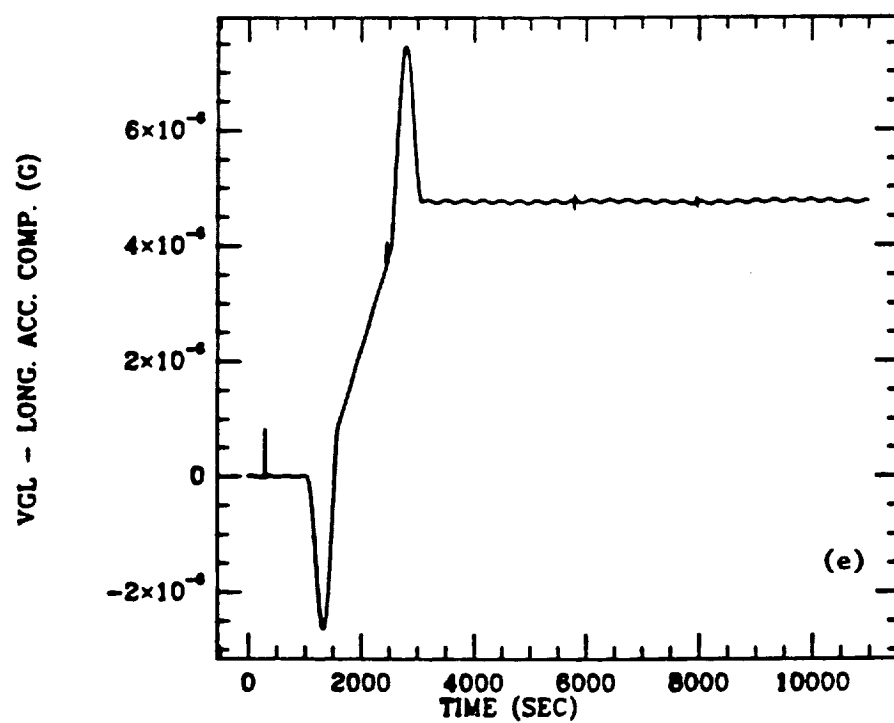
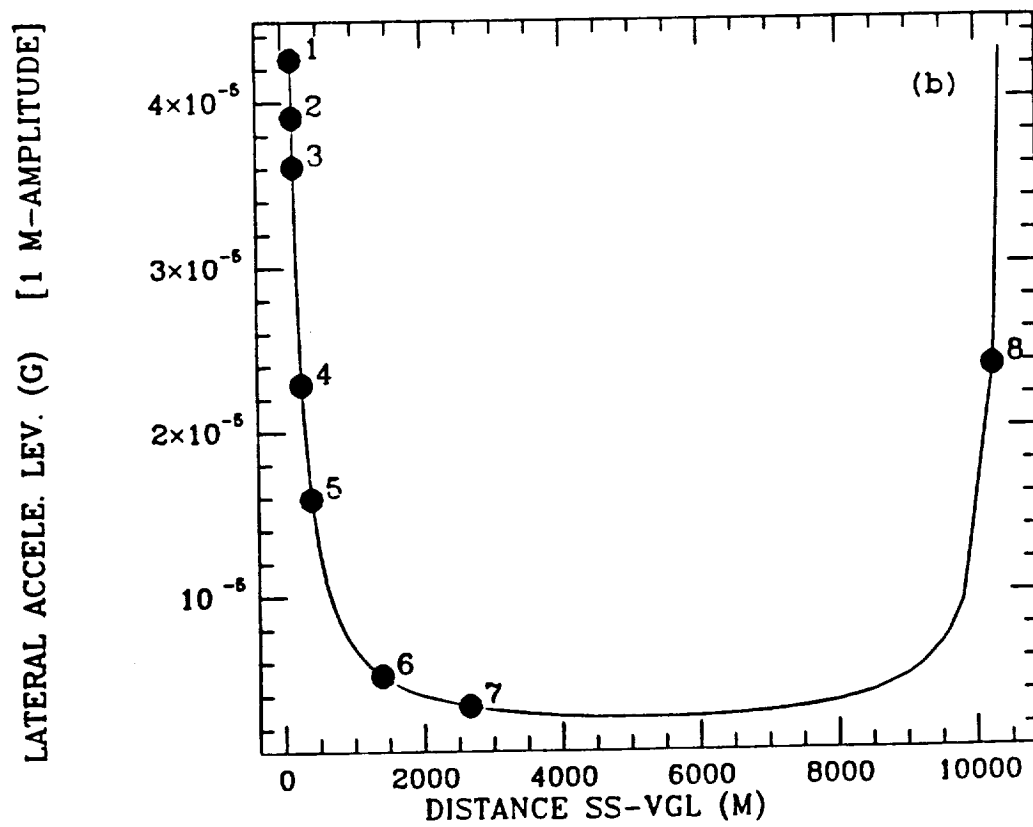
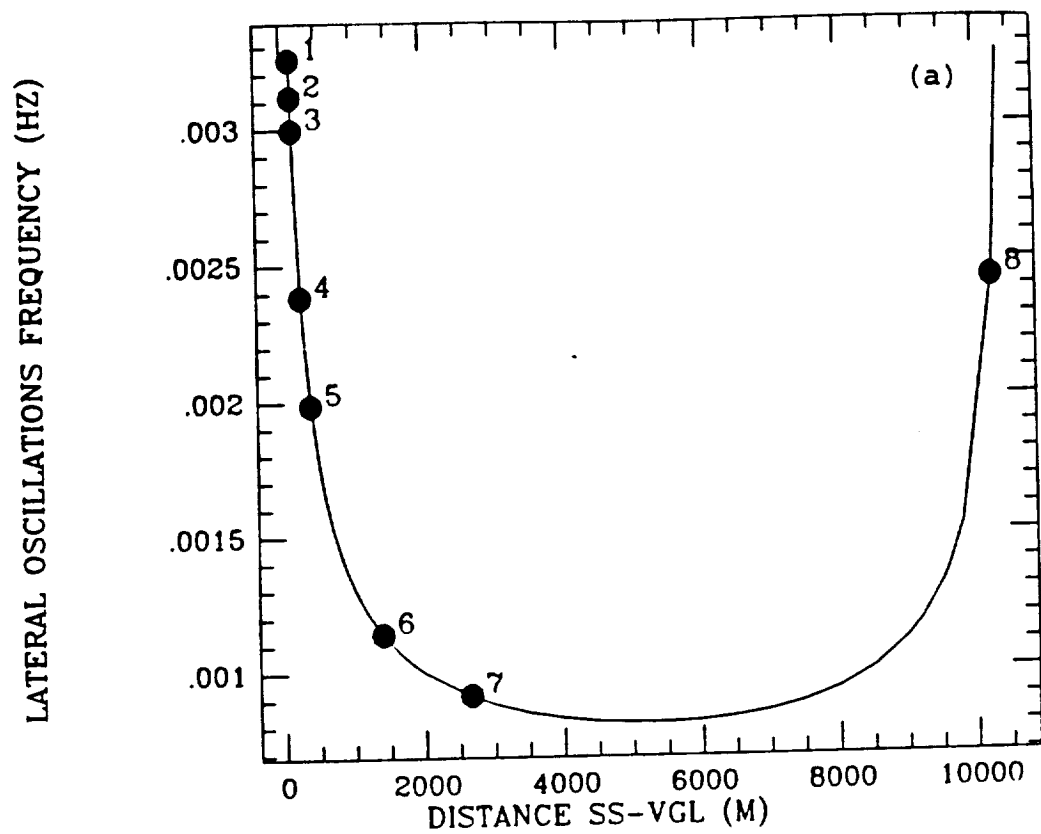


Figure 3.4(e)



Figures 3.5(a)-(b)

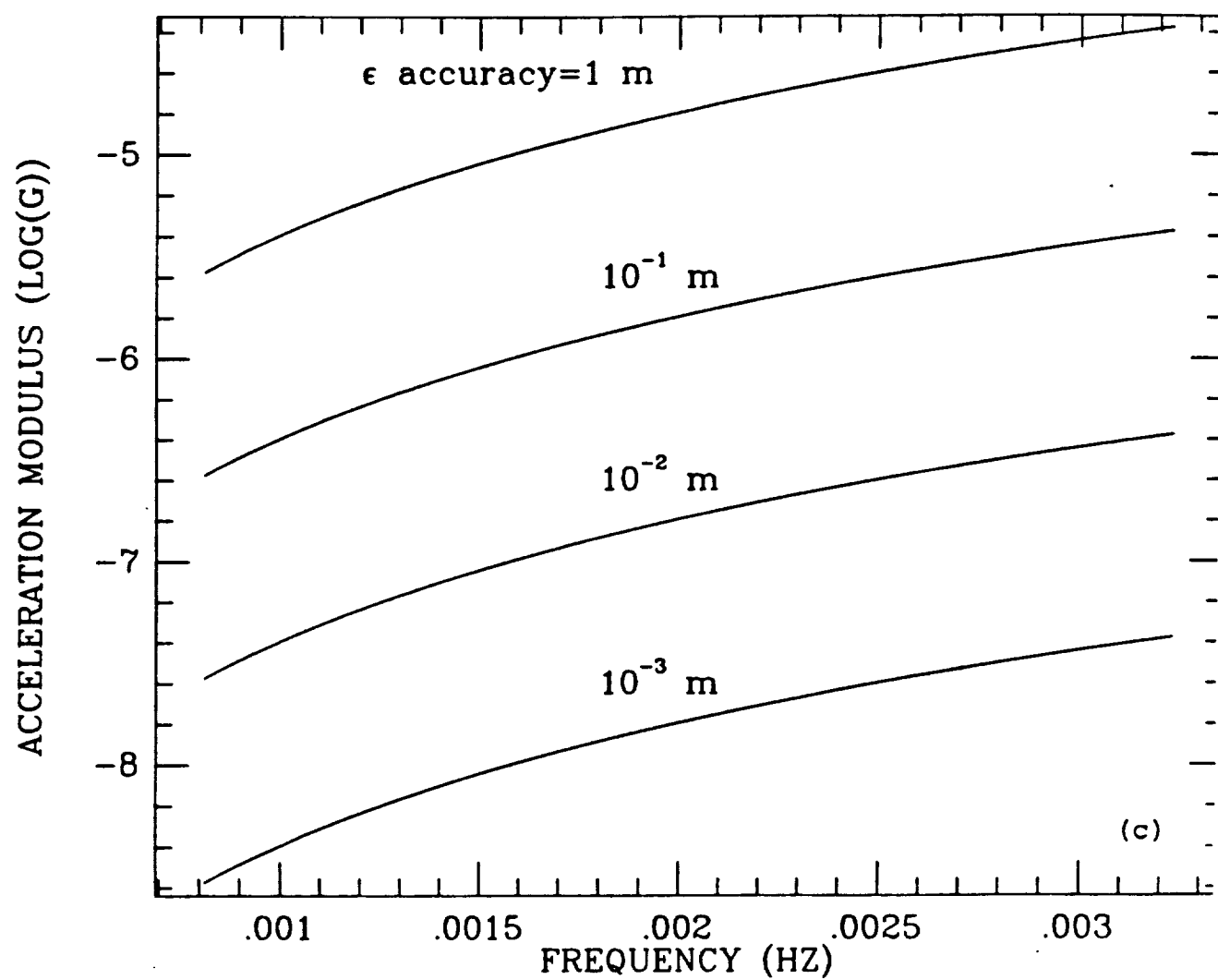
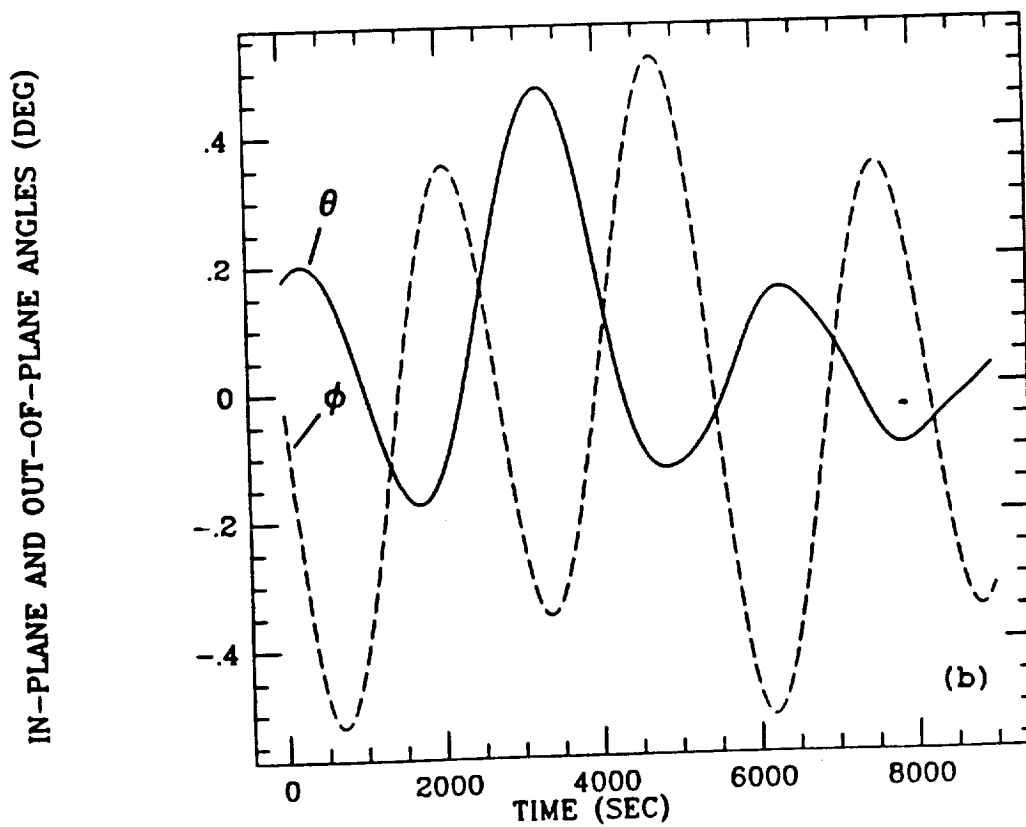
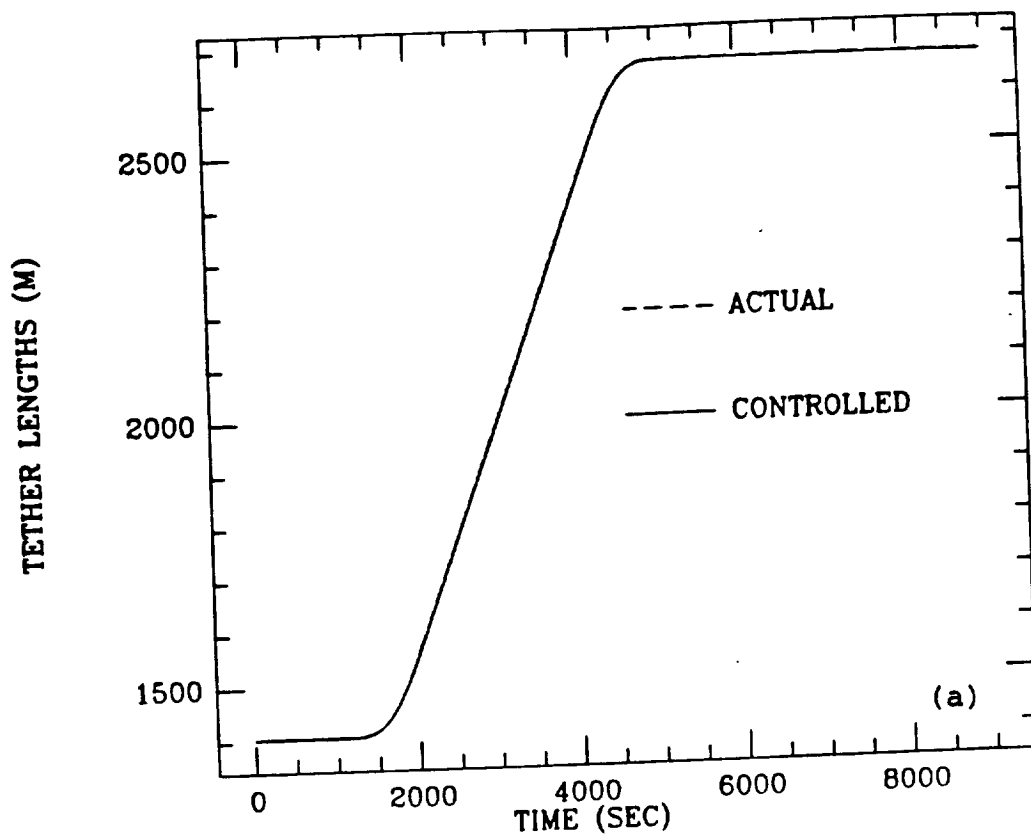
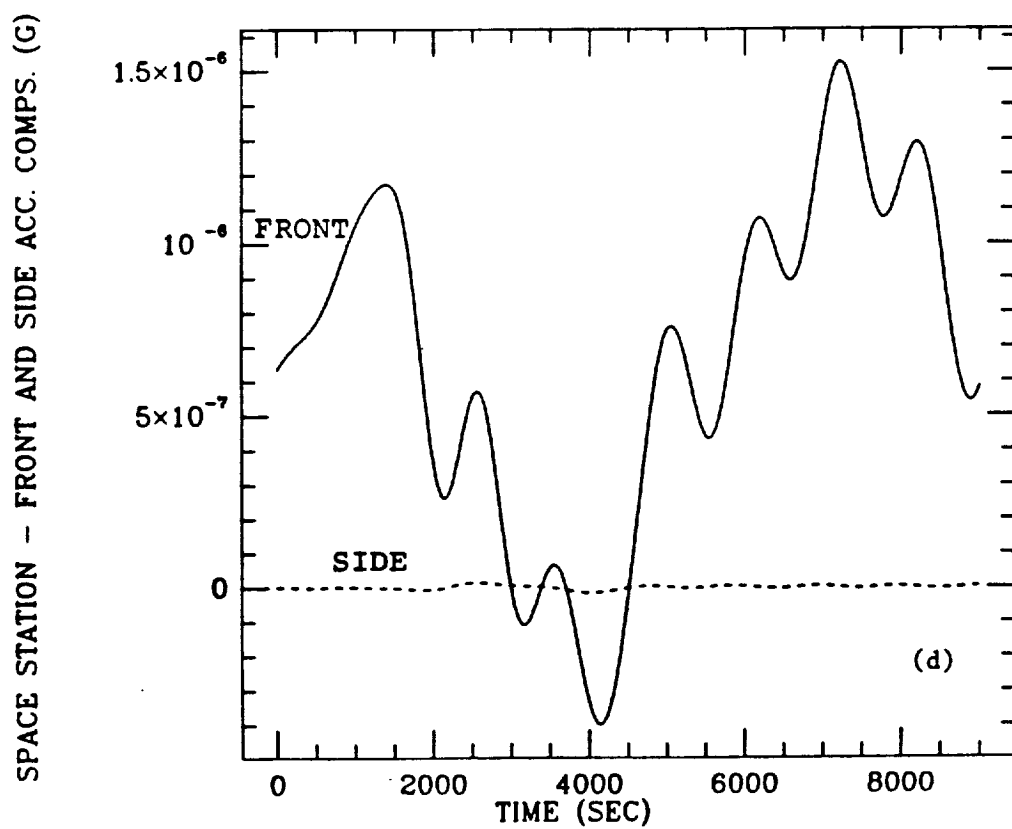
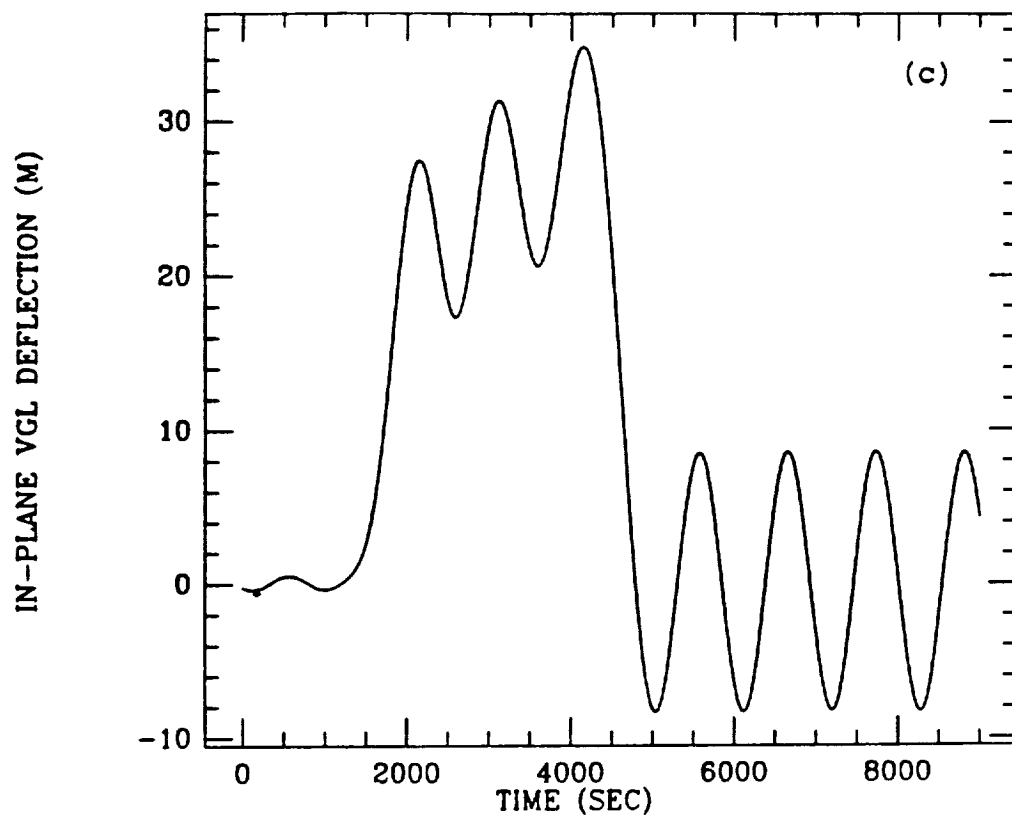


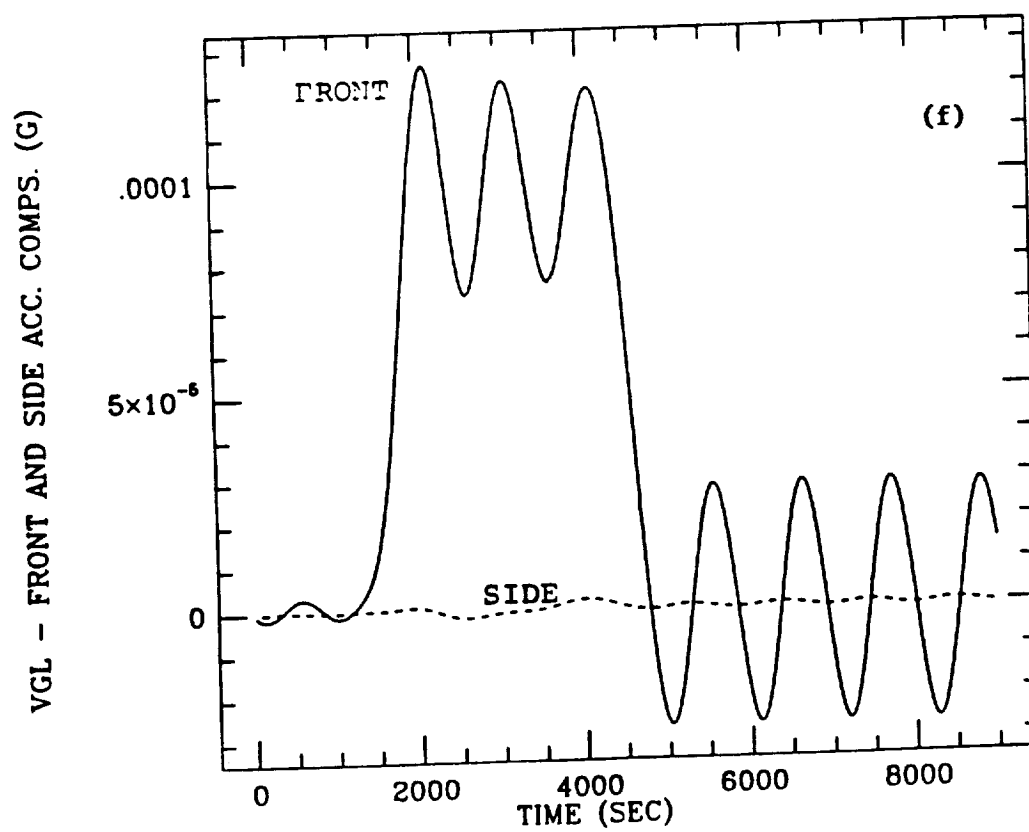
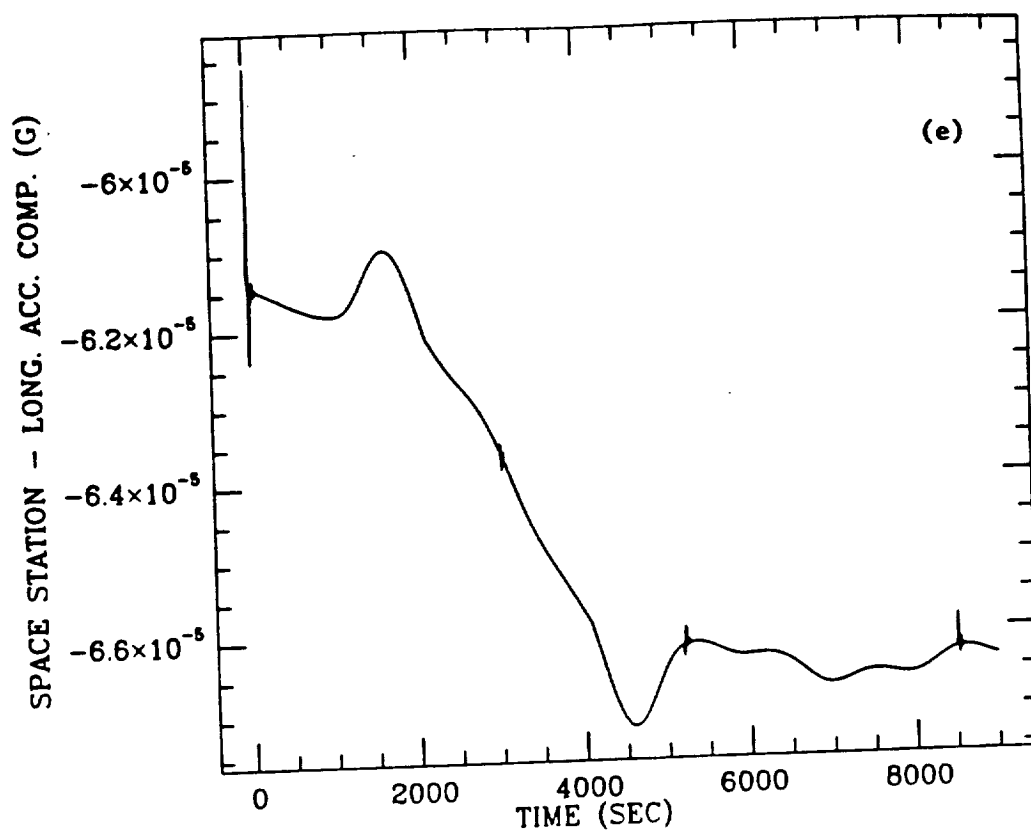
Figure 3.5(c)



Figures 3.6(a)-(b)



Figures 3.6(c)-(d)



Figures 3.6(e)-(f)

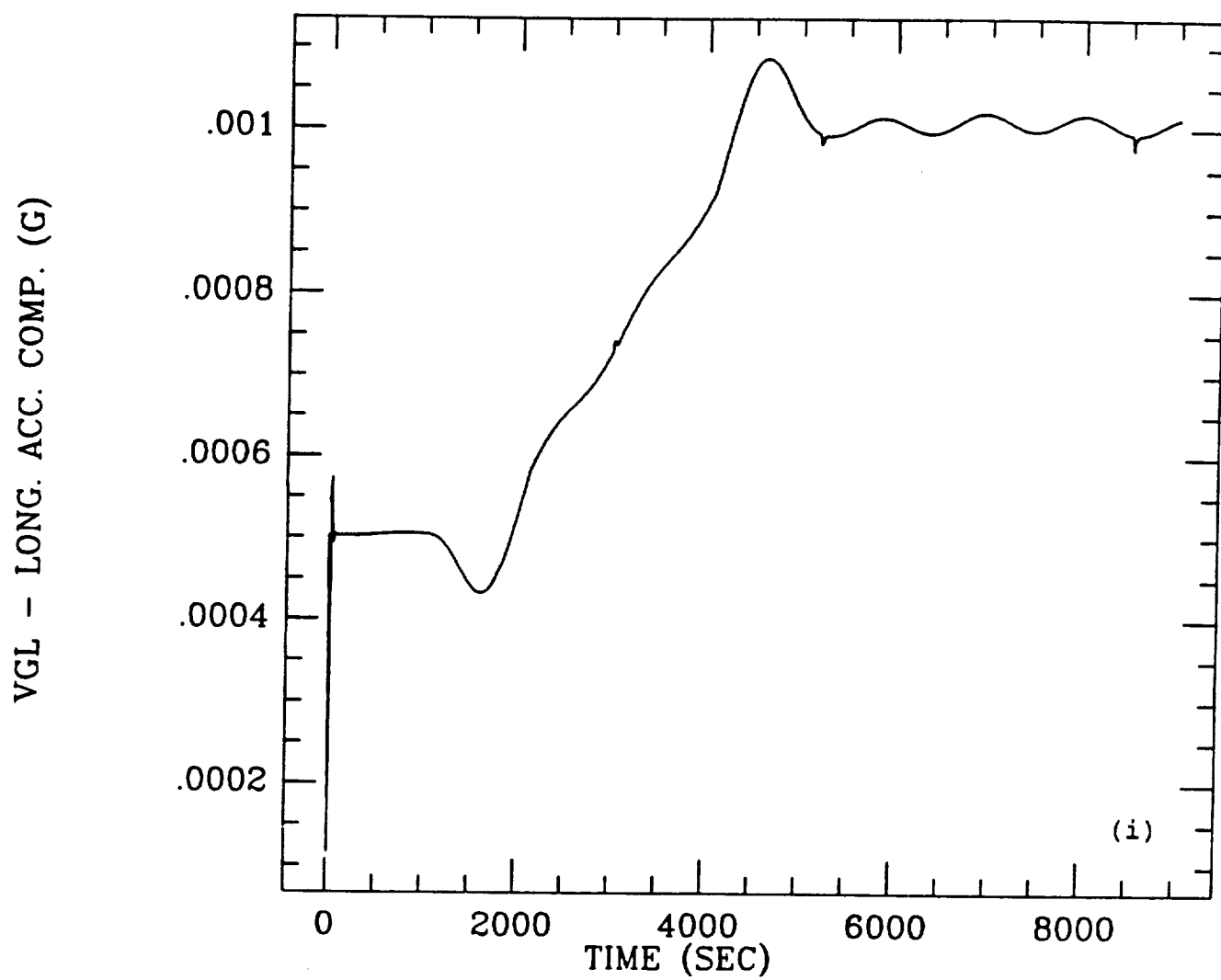
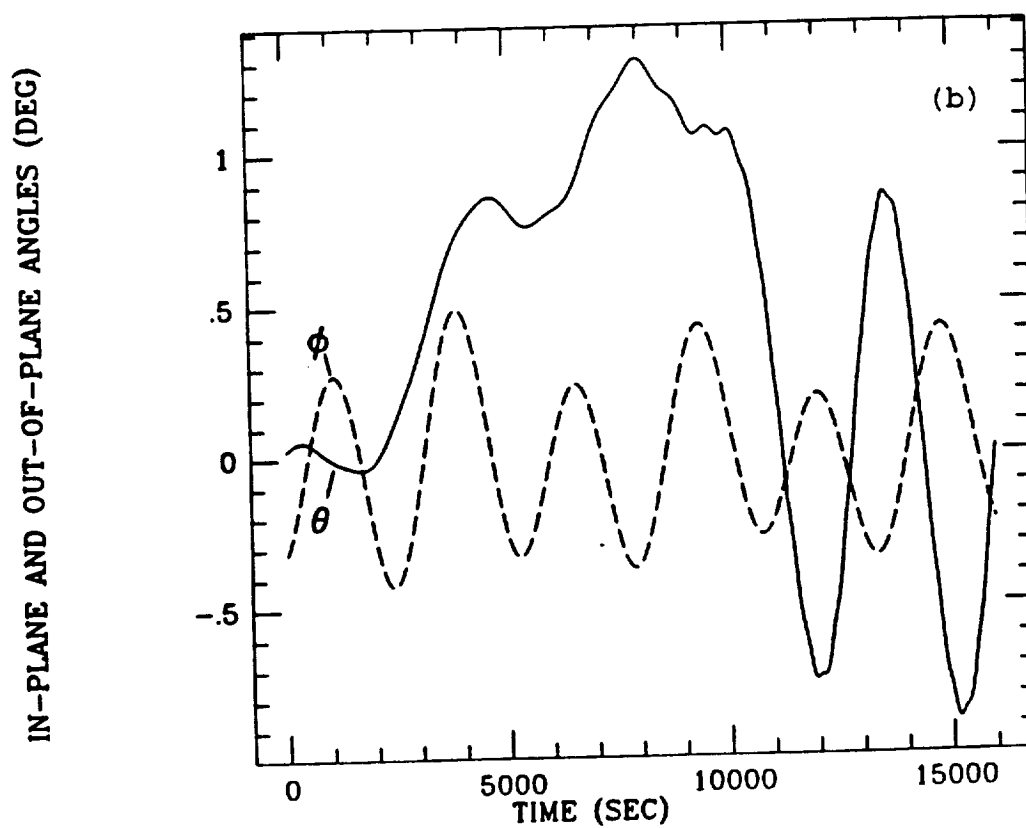
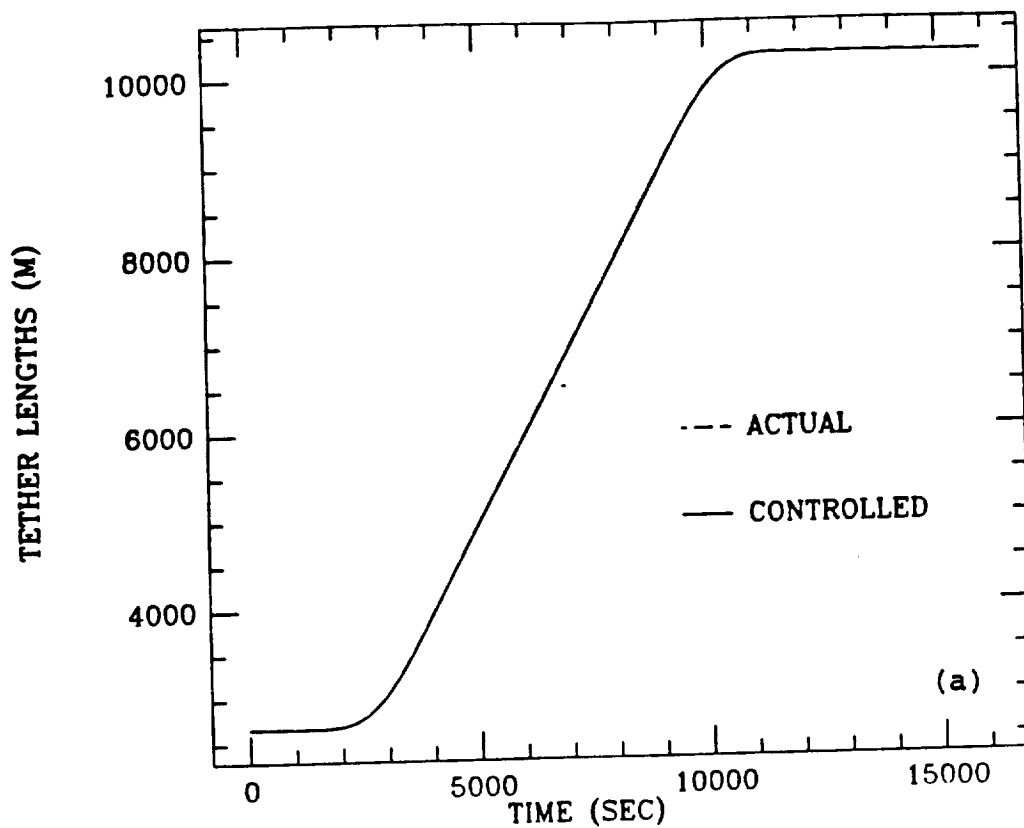
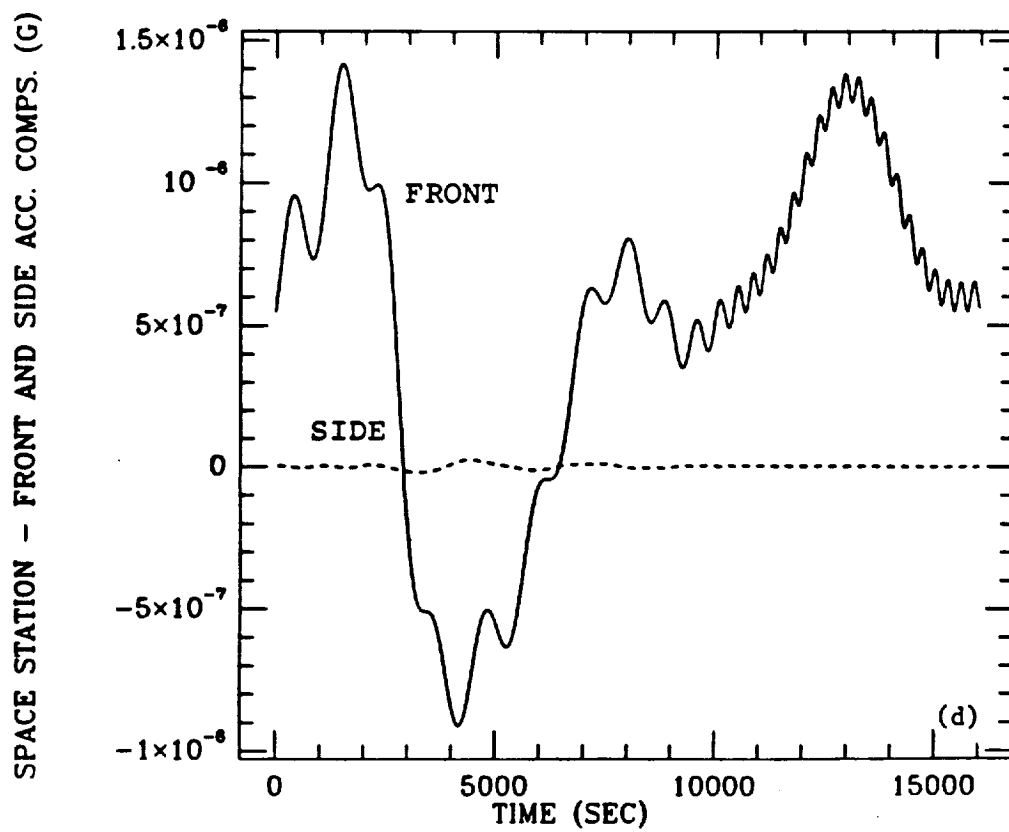
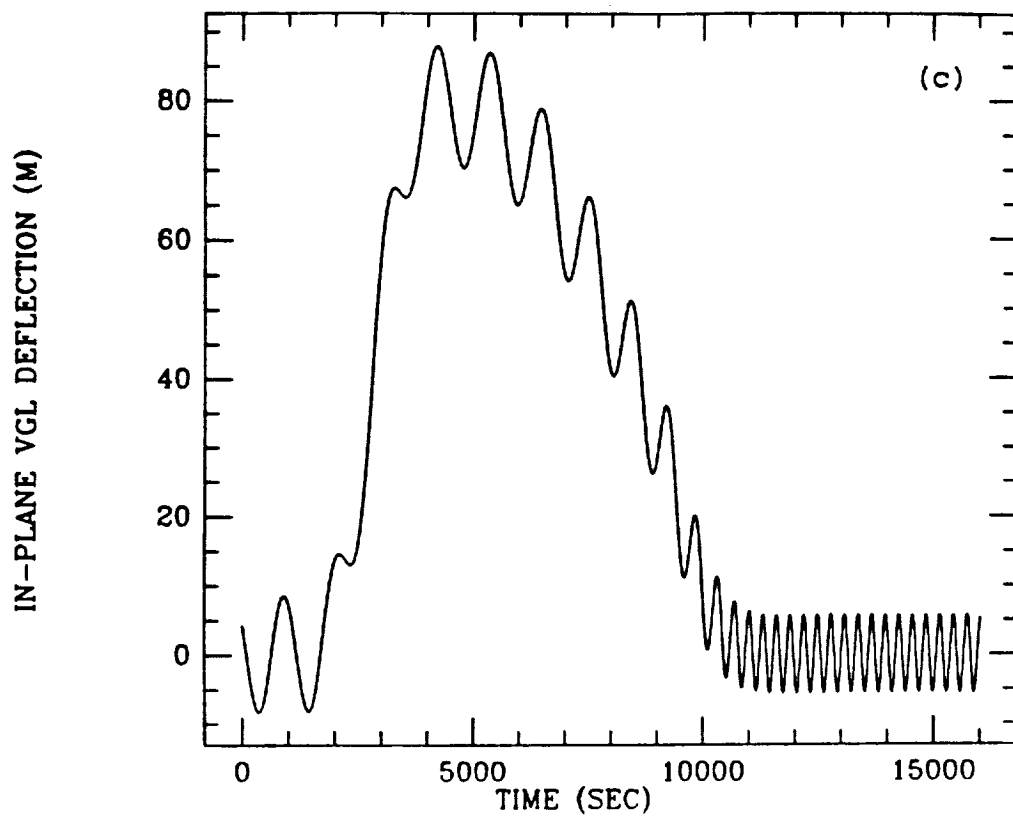
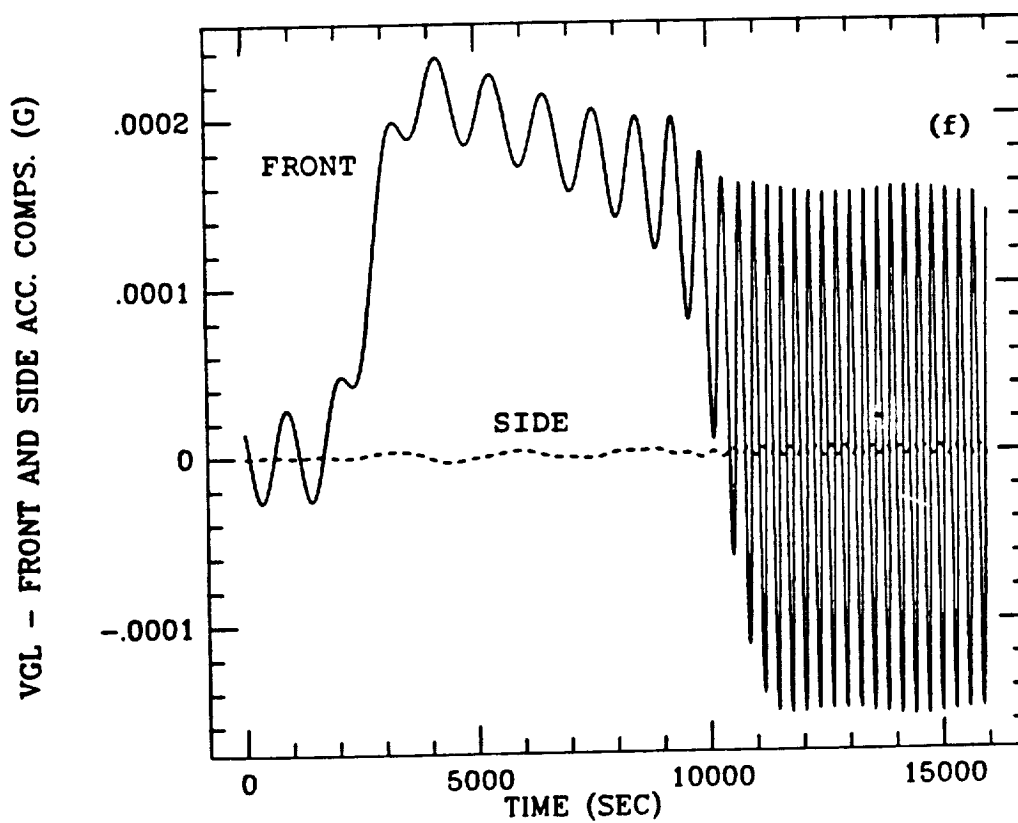
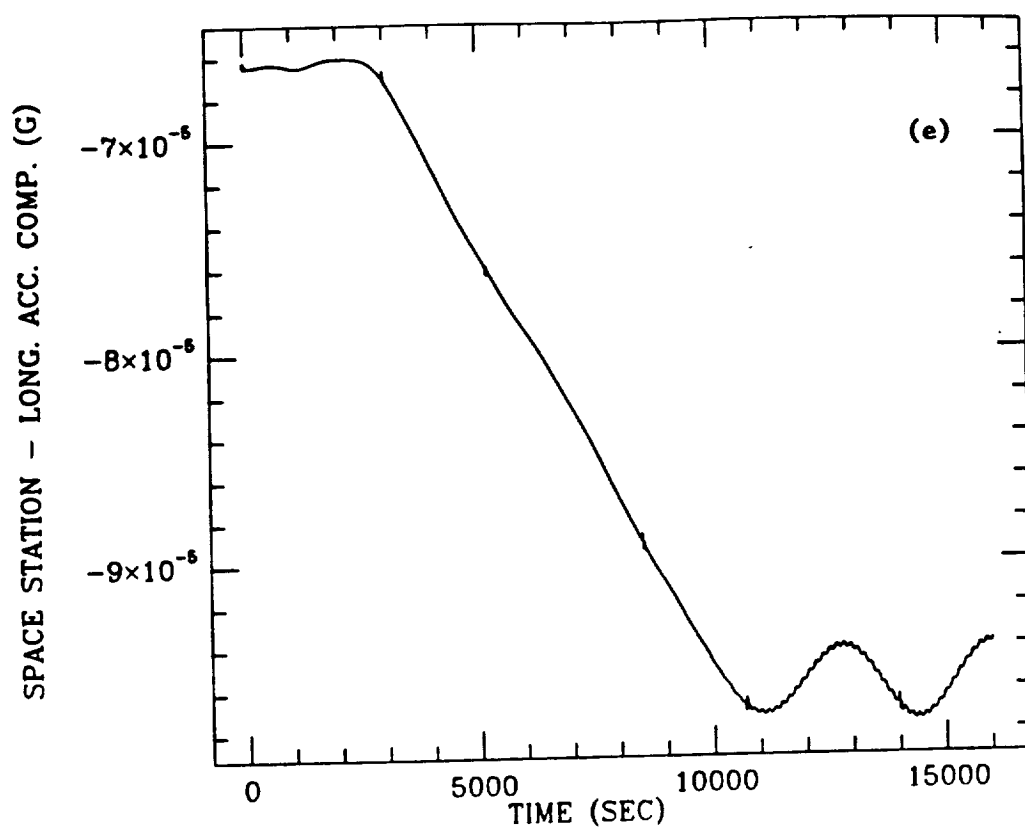


Figure 3(g)



Figures 3.7(a)-(b)

**Figures 3.7(c)-(d)**



Figures 3.7(e)-(f)

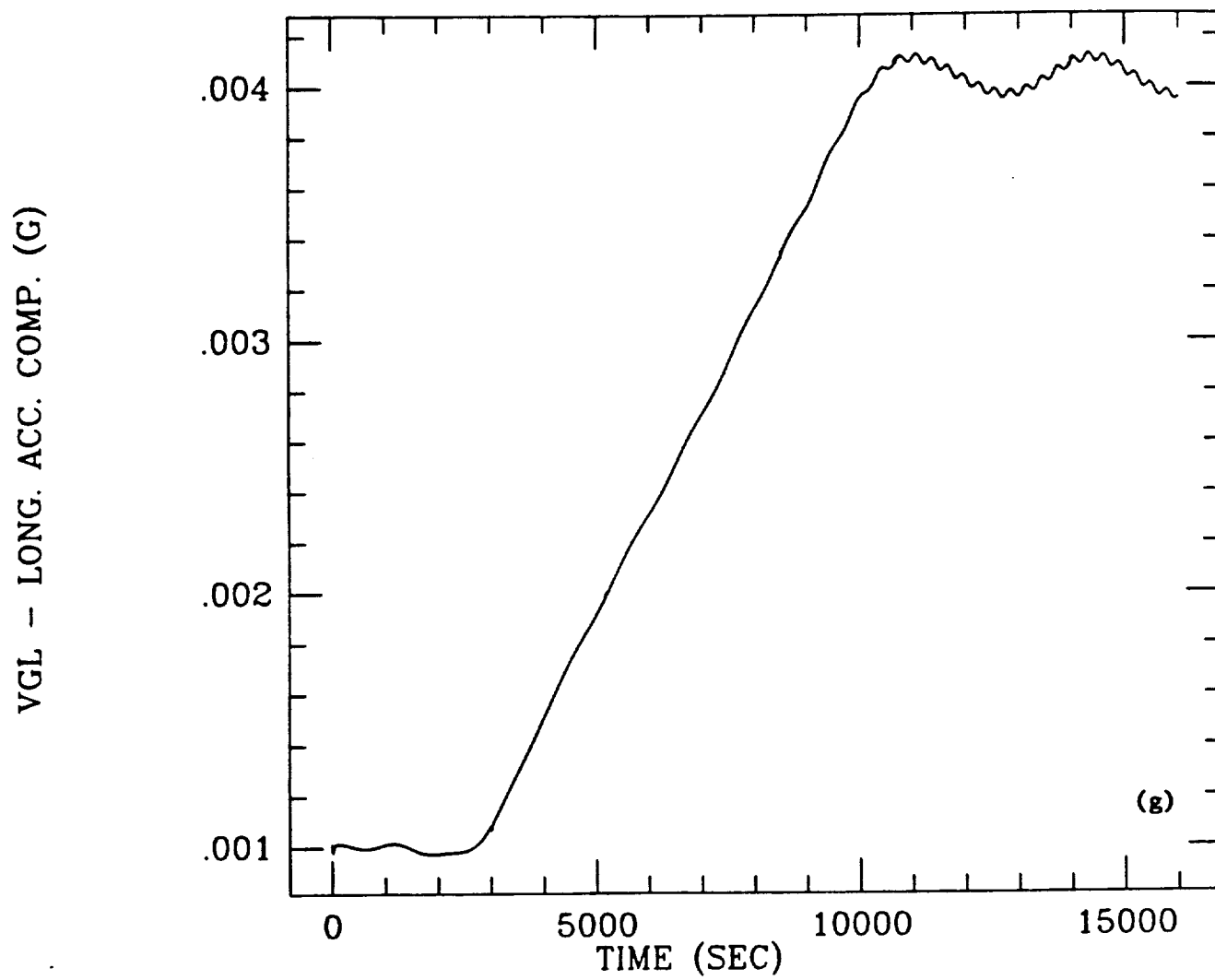
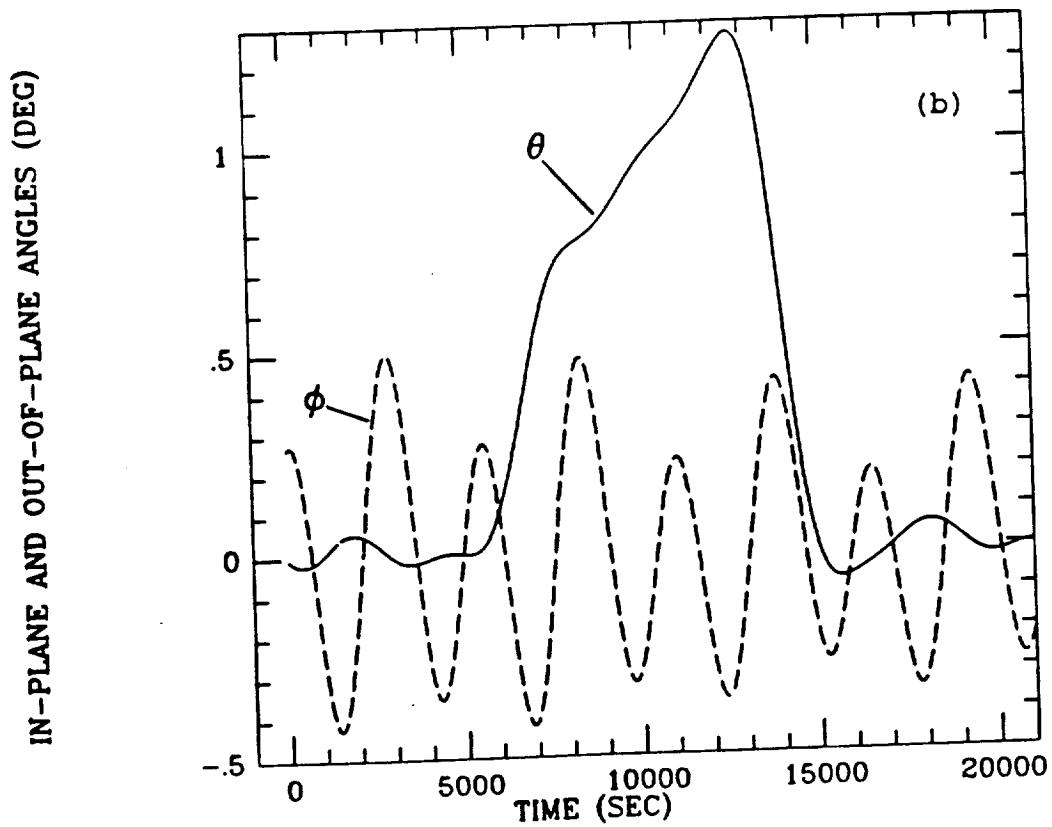
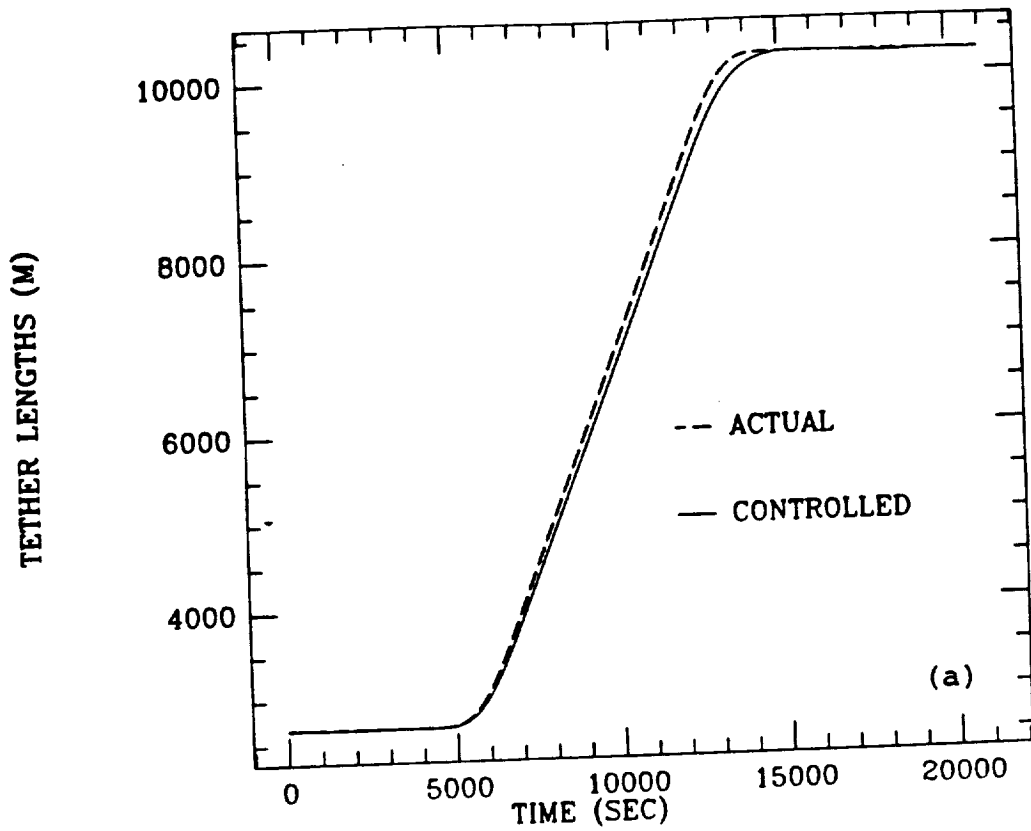
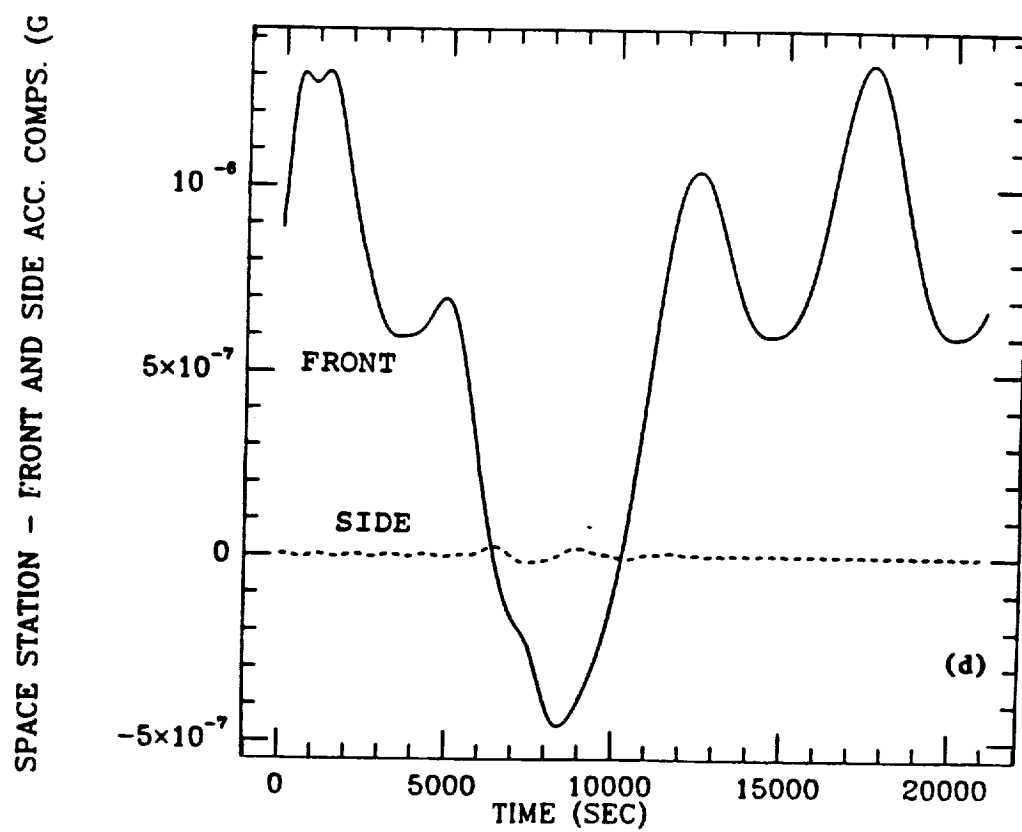
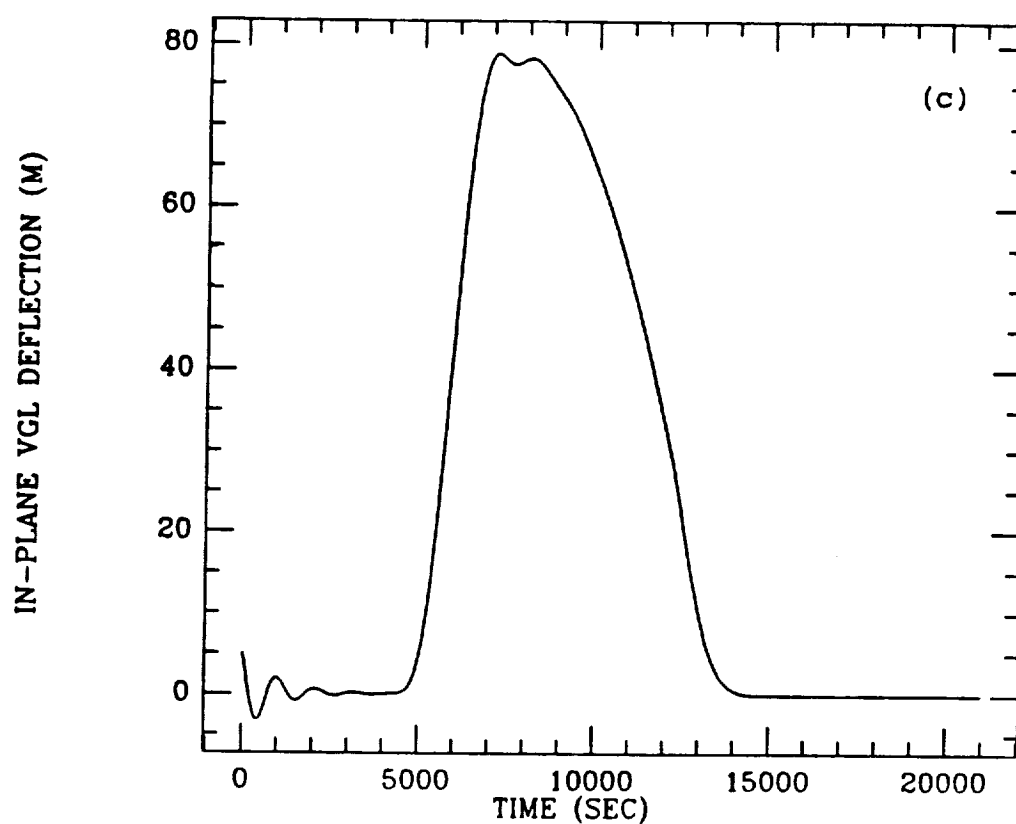


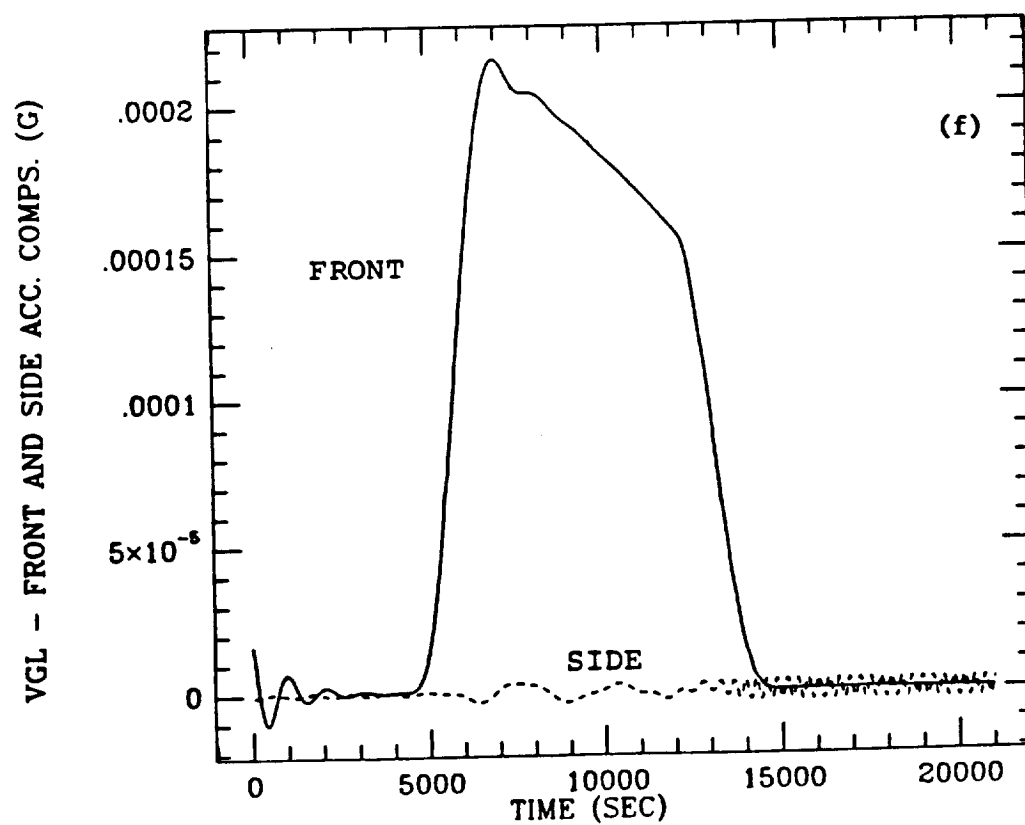
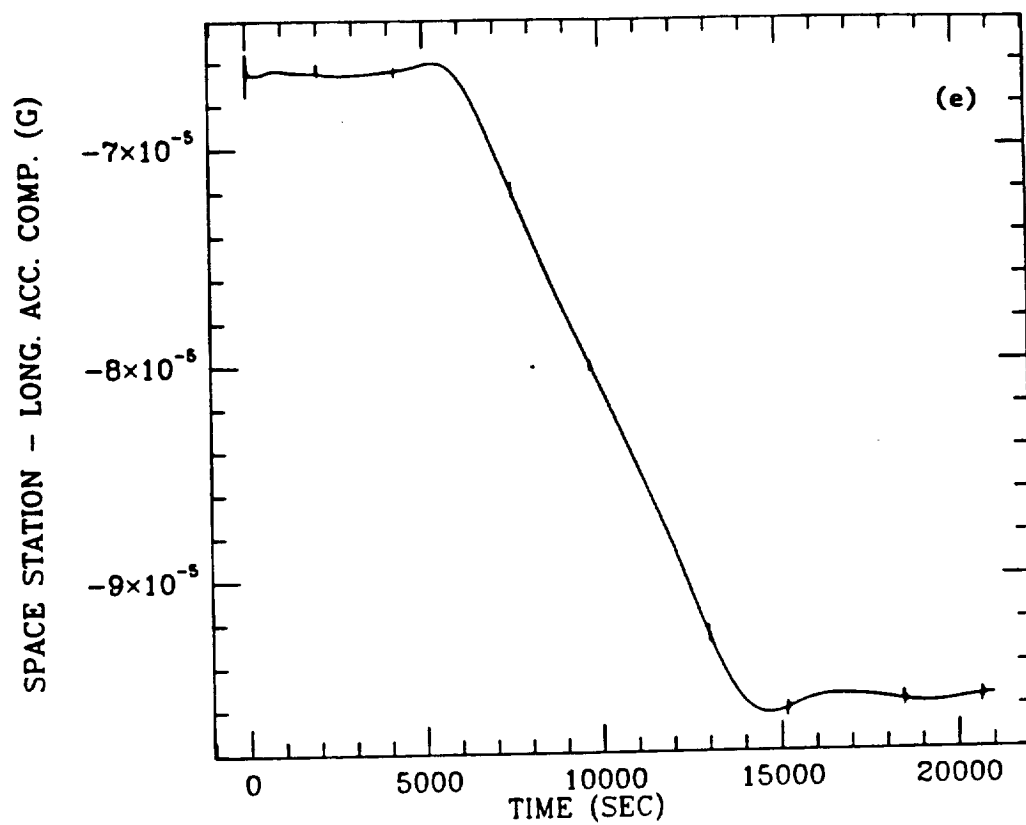
Figure 3.7(g)



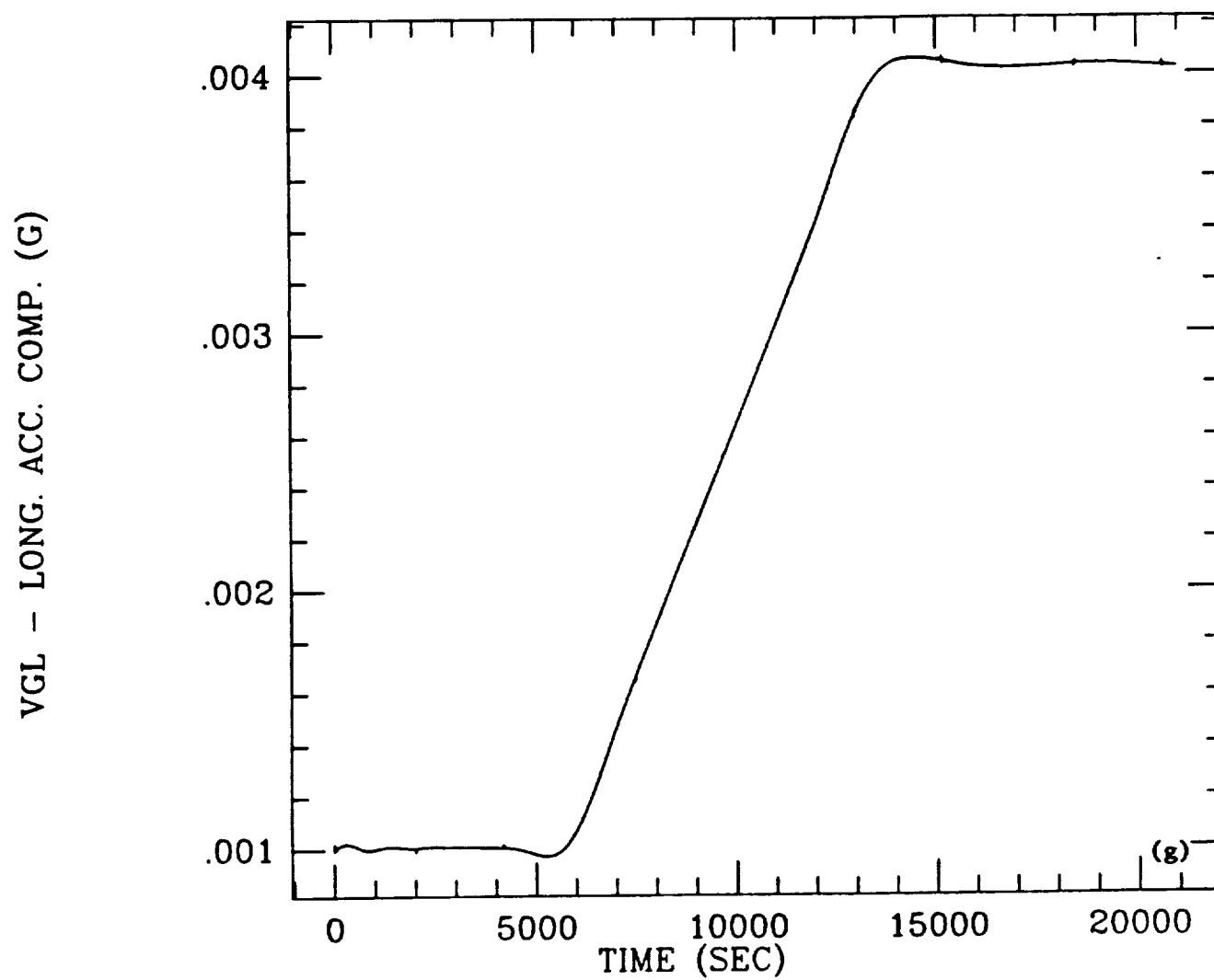
Figures 3.8(a)-(b)

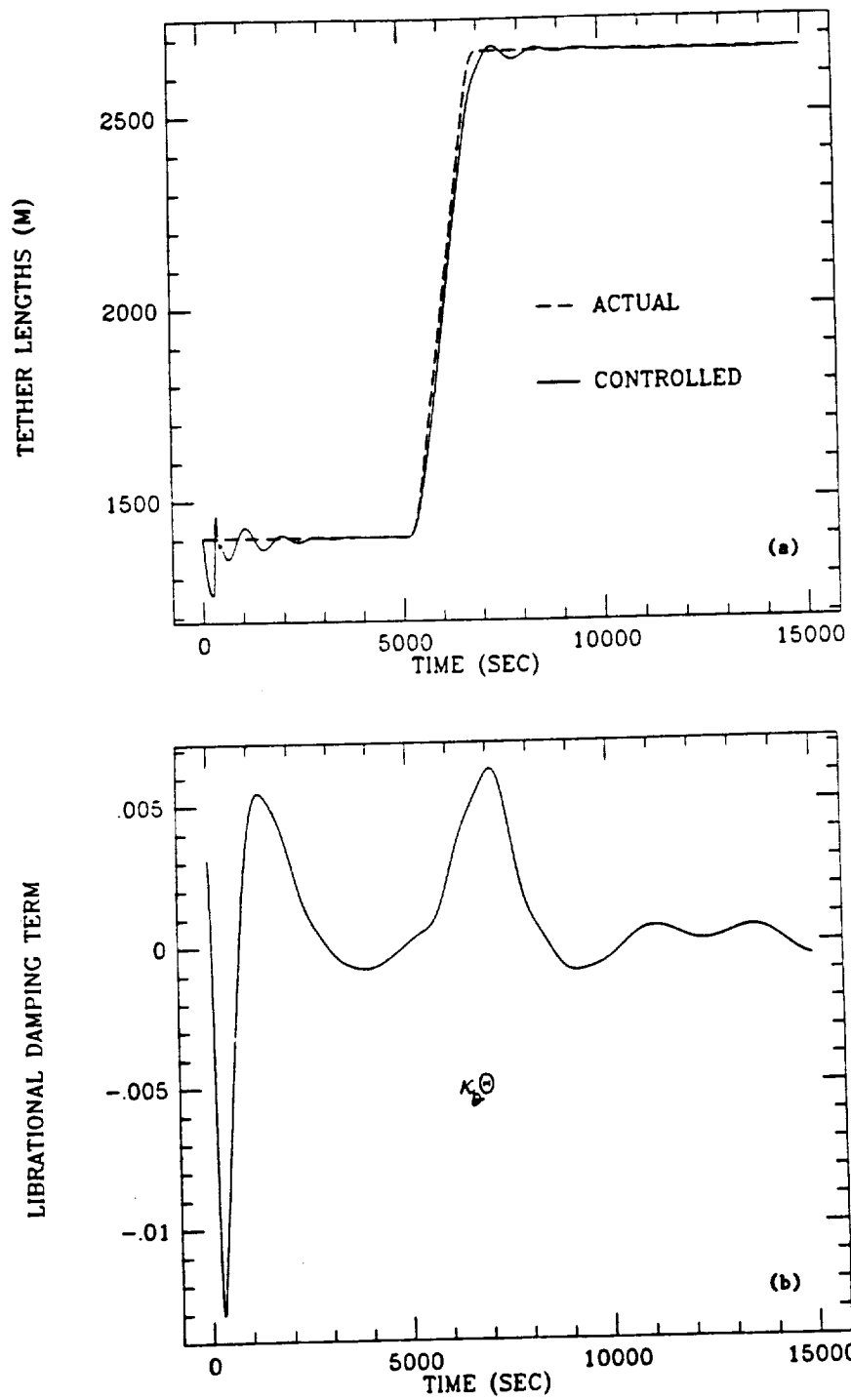


Figures 3.8(c)-(d)

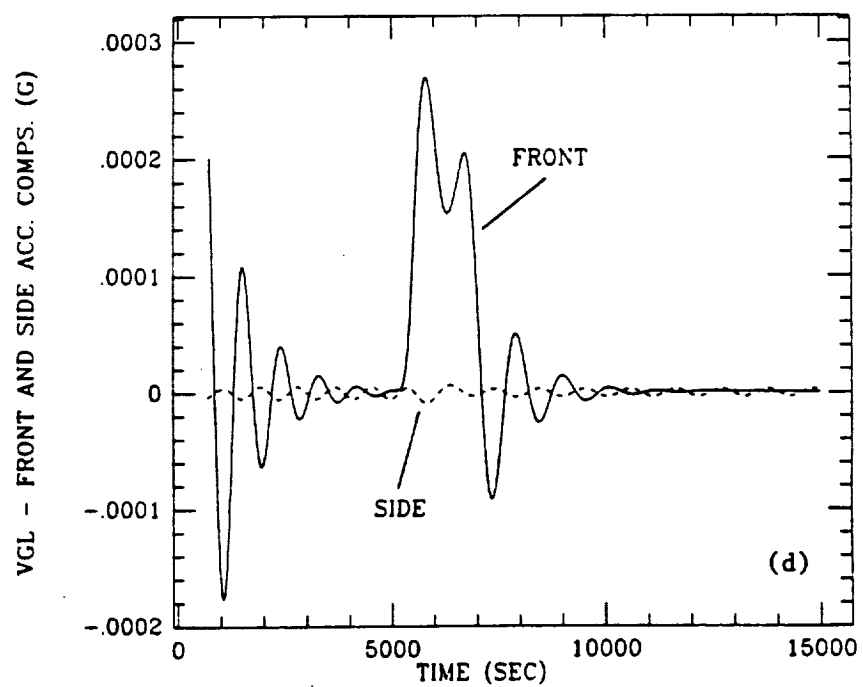
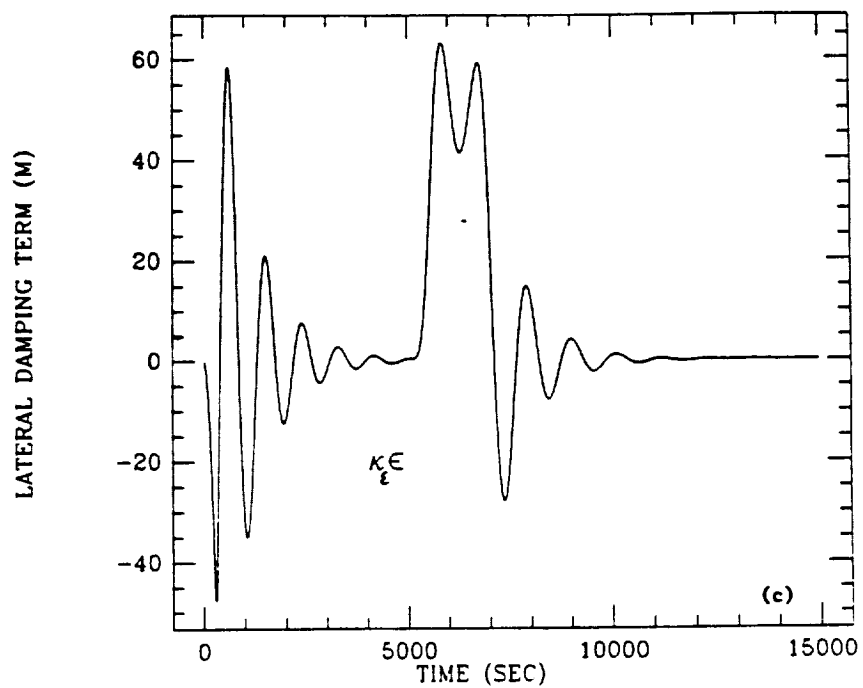


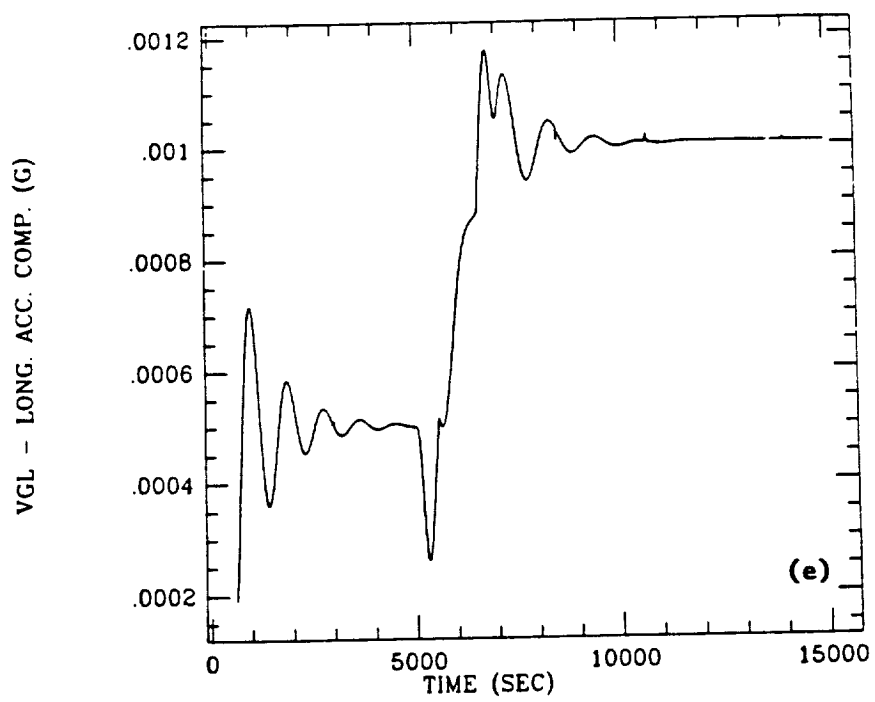
Figures 3.8(e)-(f)

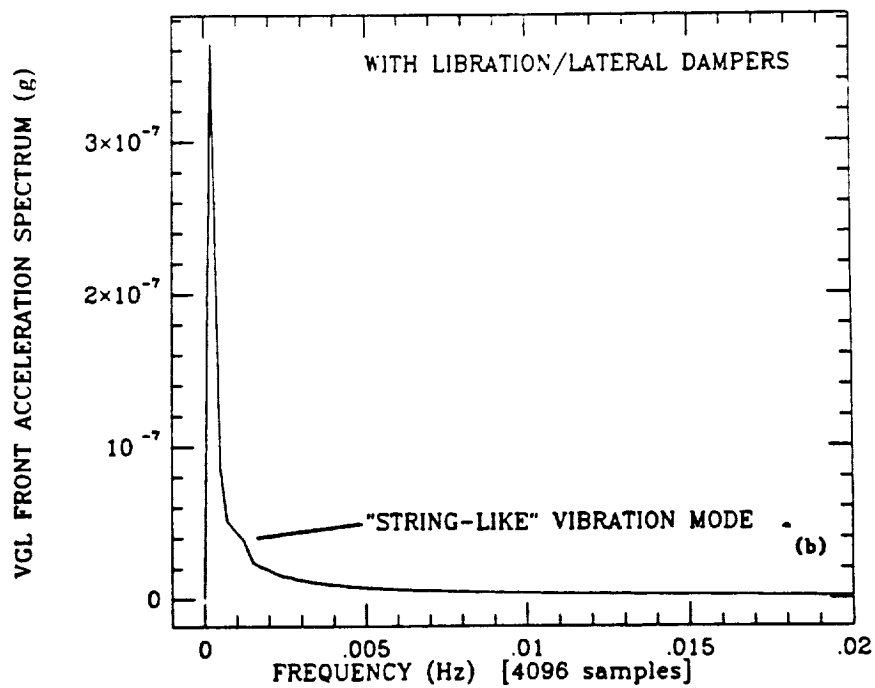
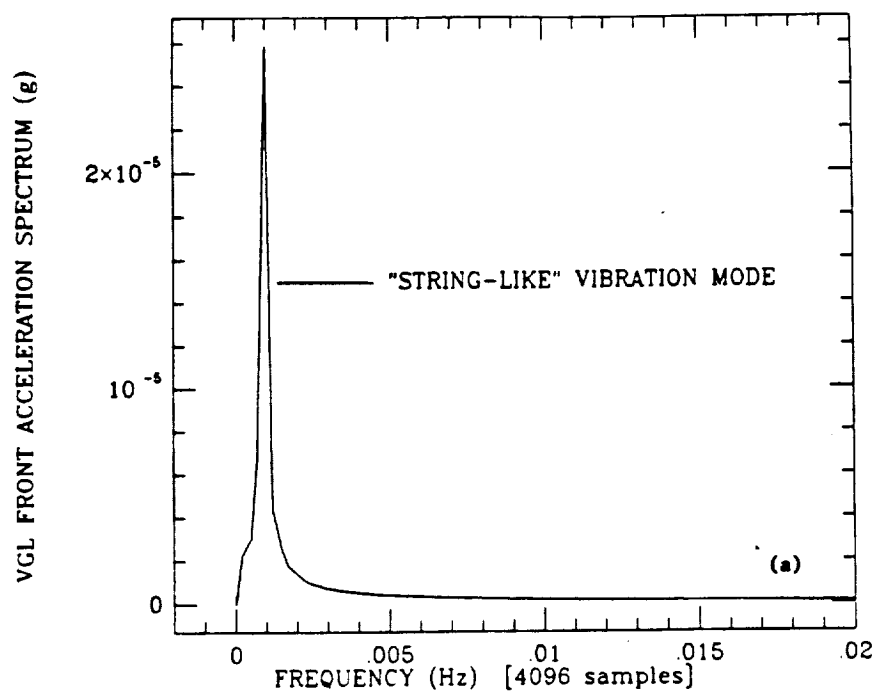
**Figure 3.8(g)**

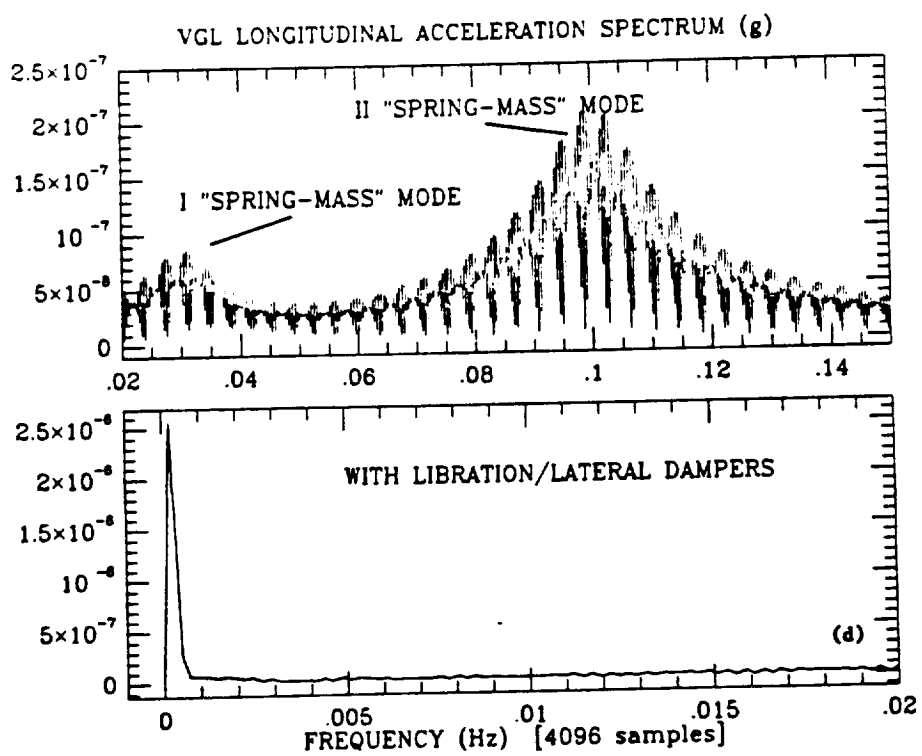
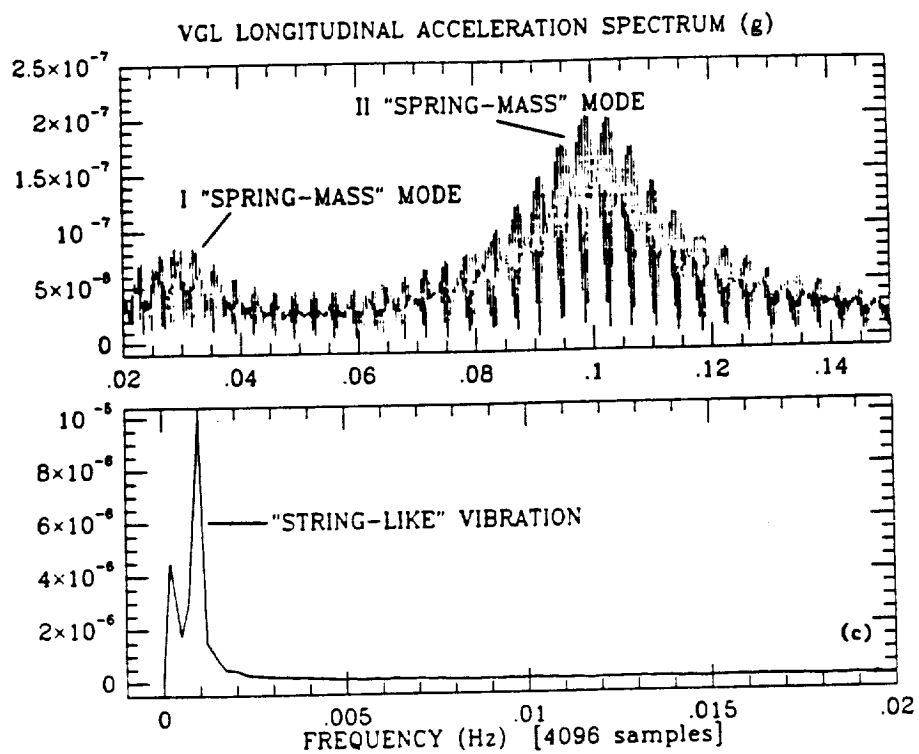


Figures 3.9(a)-(b)

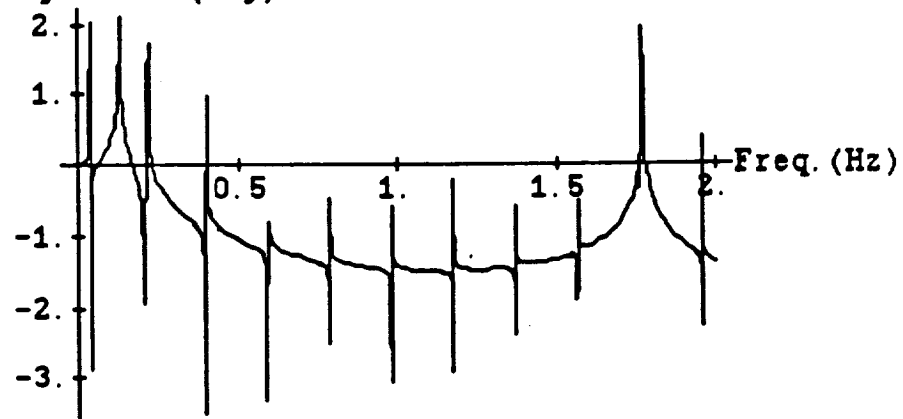
**Figures 3.9(c)-(d)**

**Figure 3.9(e)**

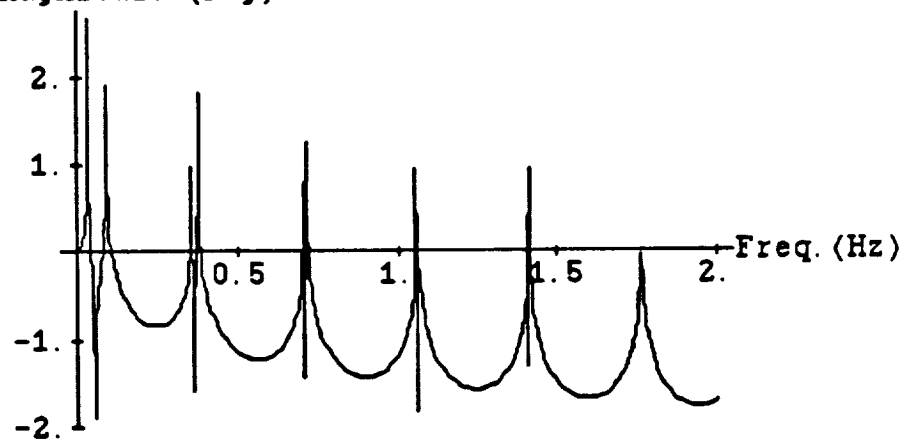
**Figures 3.10(a)-(b)**

**Figures 3.10(c)-(d)**

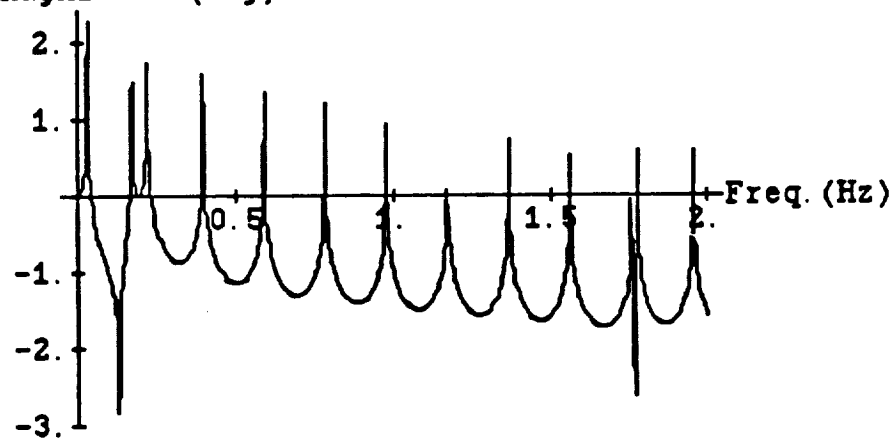
EL FRF Magnitude (Log)

 $\lambda_1 = 0.1$ (a)

EL FRF Magnitude (Log)

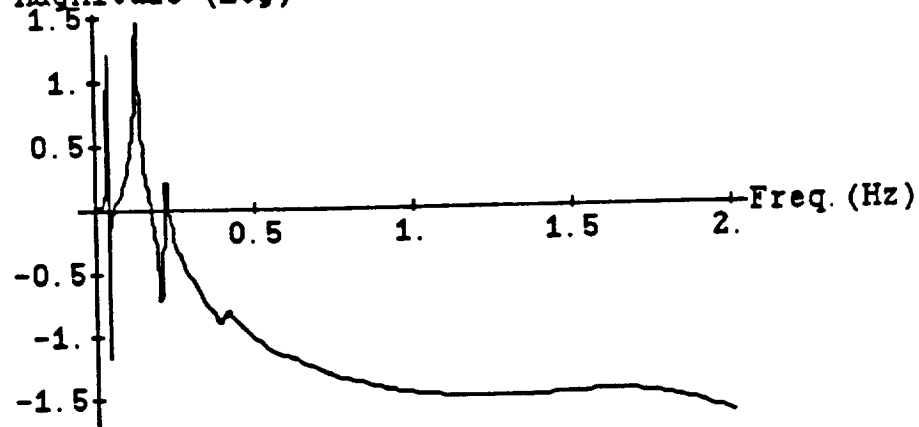
 $\lambda_1 = 0.5$ (b)

EL FRF Magnitude (Log)

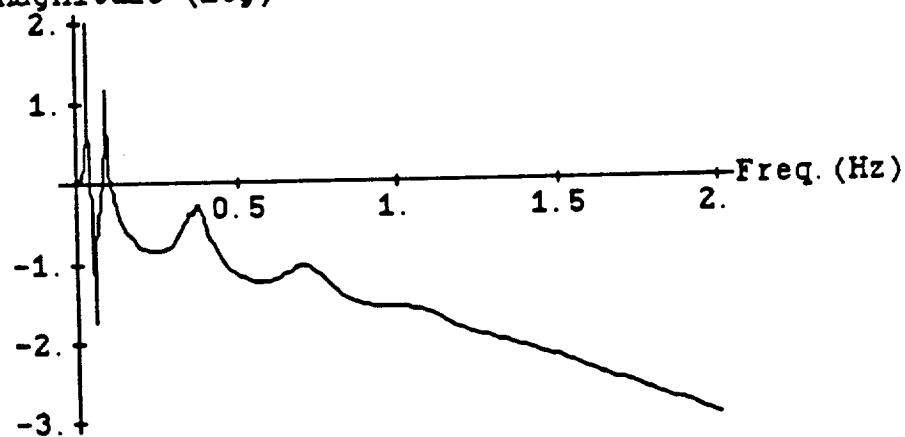
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Figures 3.11(a)-(c)

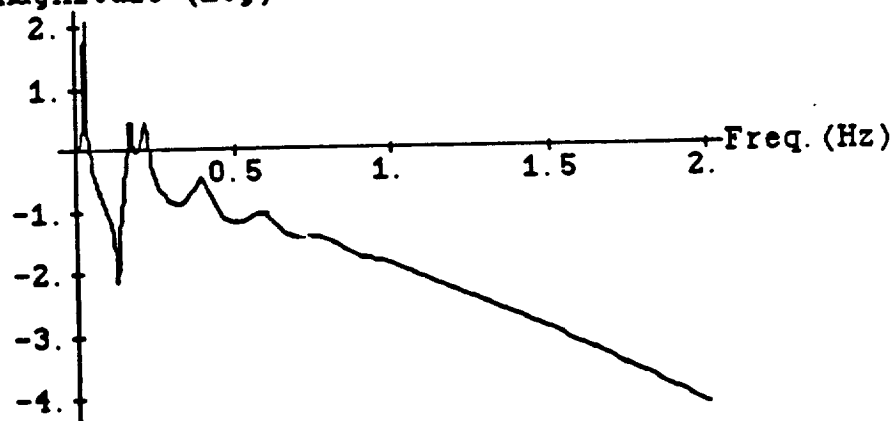
EL, FRF Magnitude (Log)

 $\lambda_1 = 0.1$ (a)

EL, FRF Magnitude (Log)

 $\lambda_1 = 0.5$ (b)

EL, FRF Magnitude (Log)

 $\lambda_1 = 0.9$ (c)

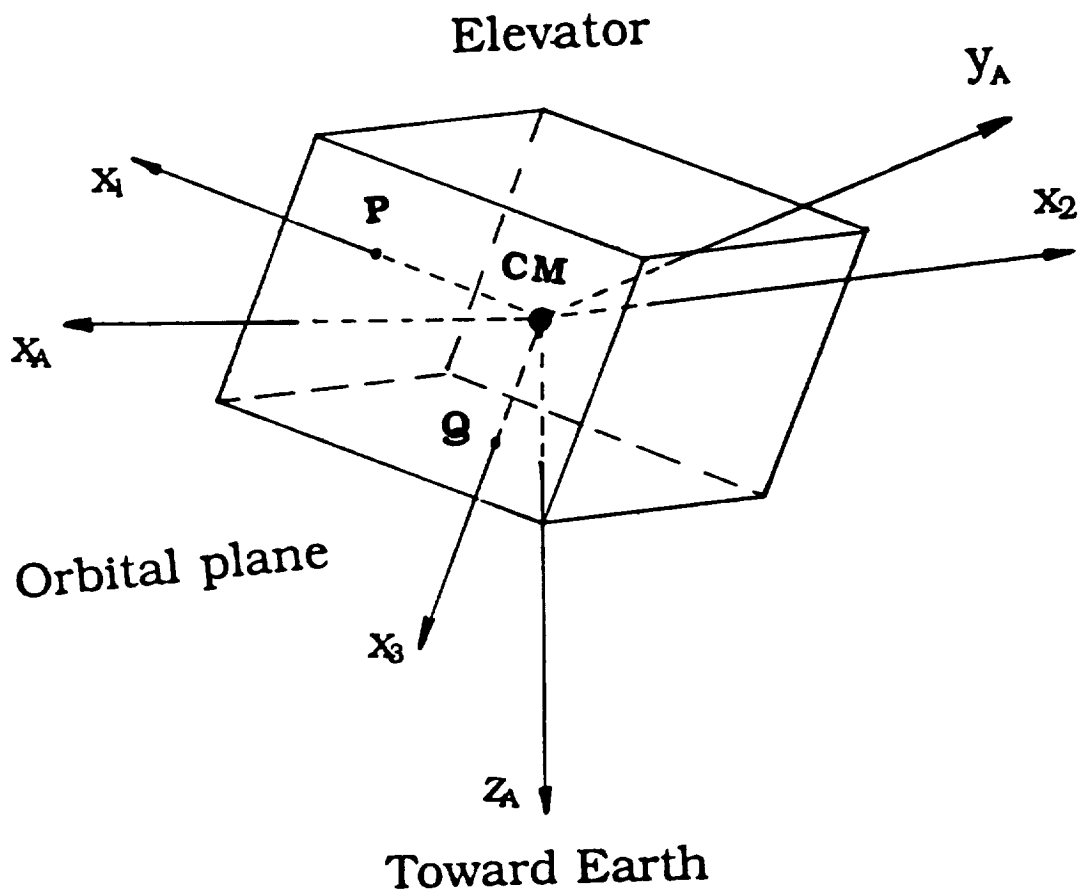
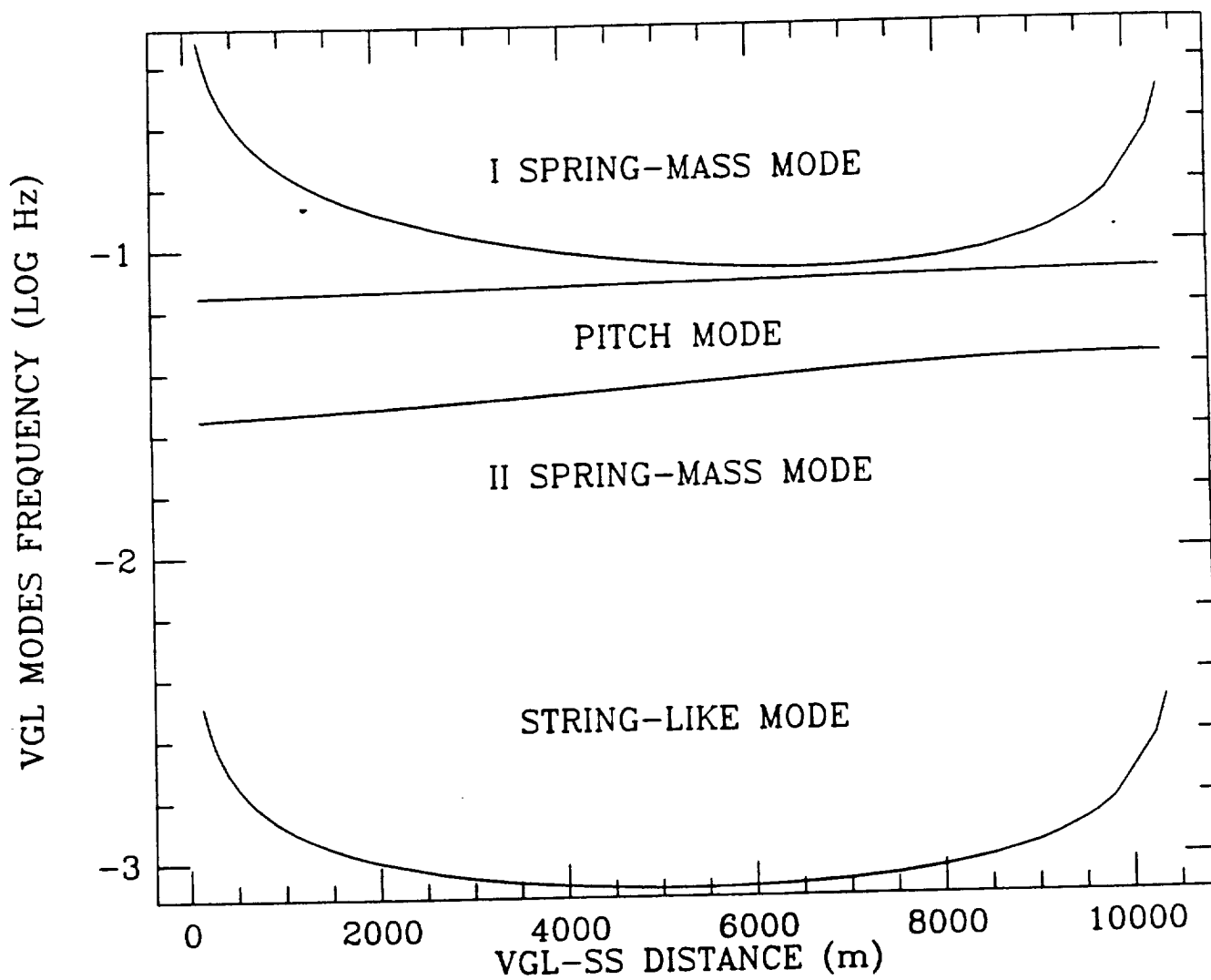
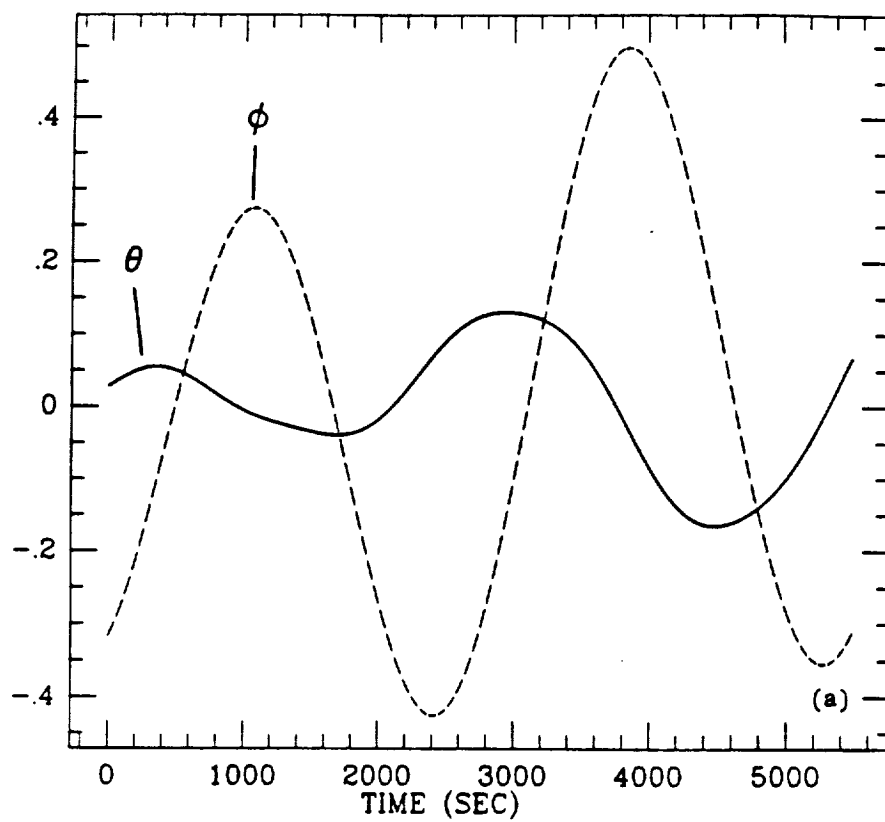


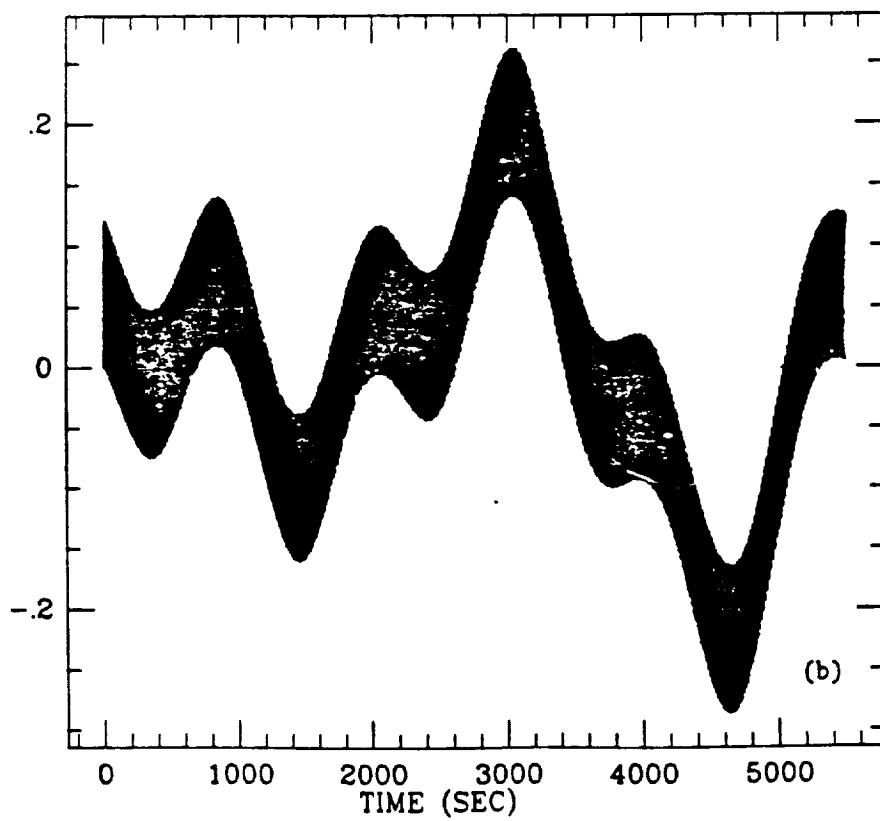
Figure 3.13

**Figure 3.14**

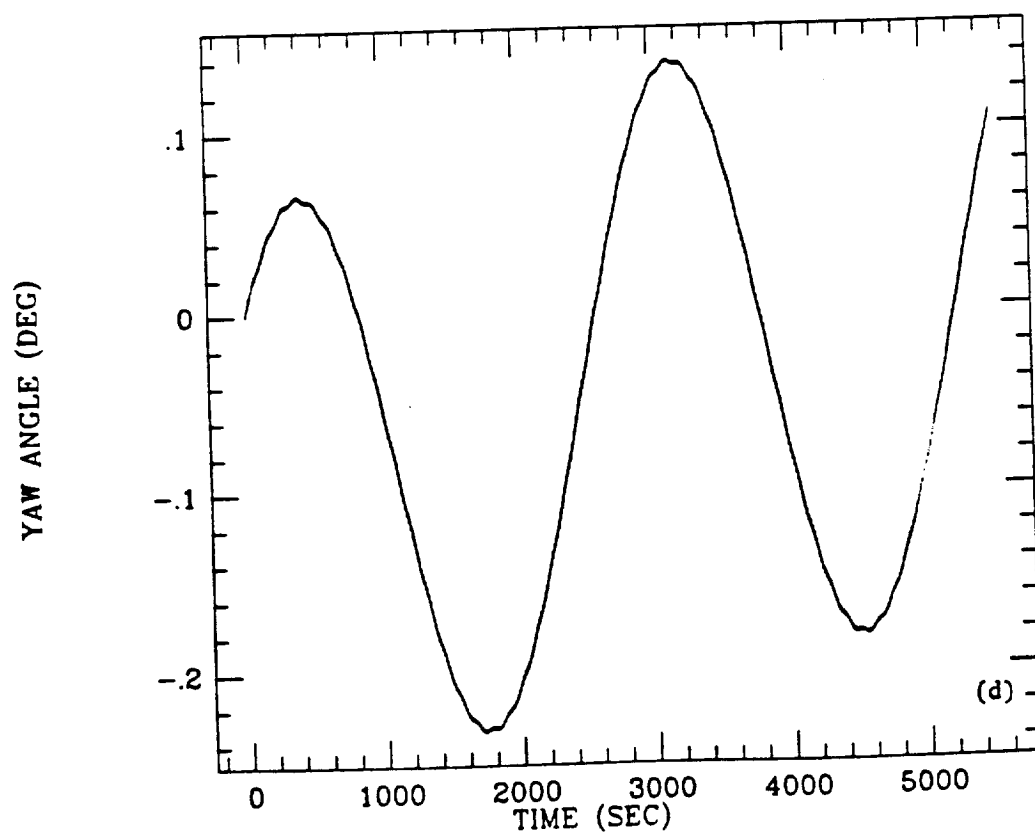
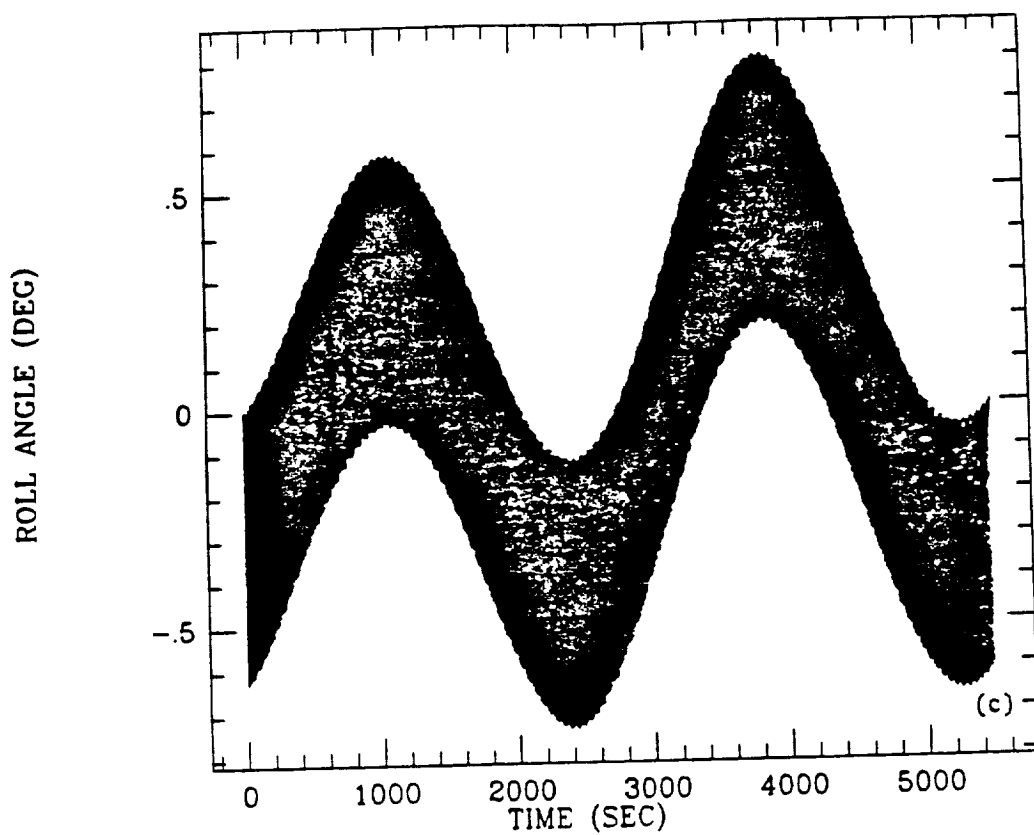
IN-PLANE AND OUT-OF-PLANE ANGLES (DEG)

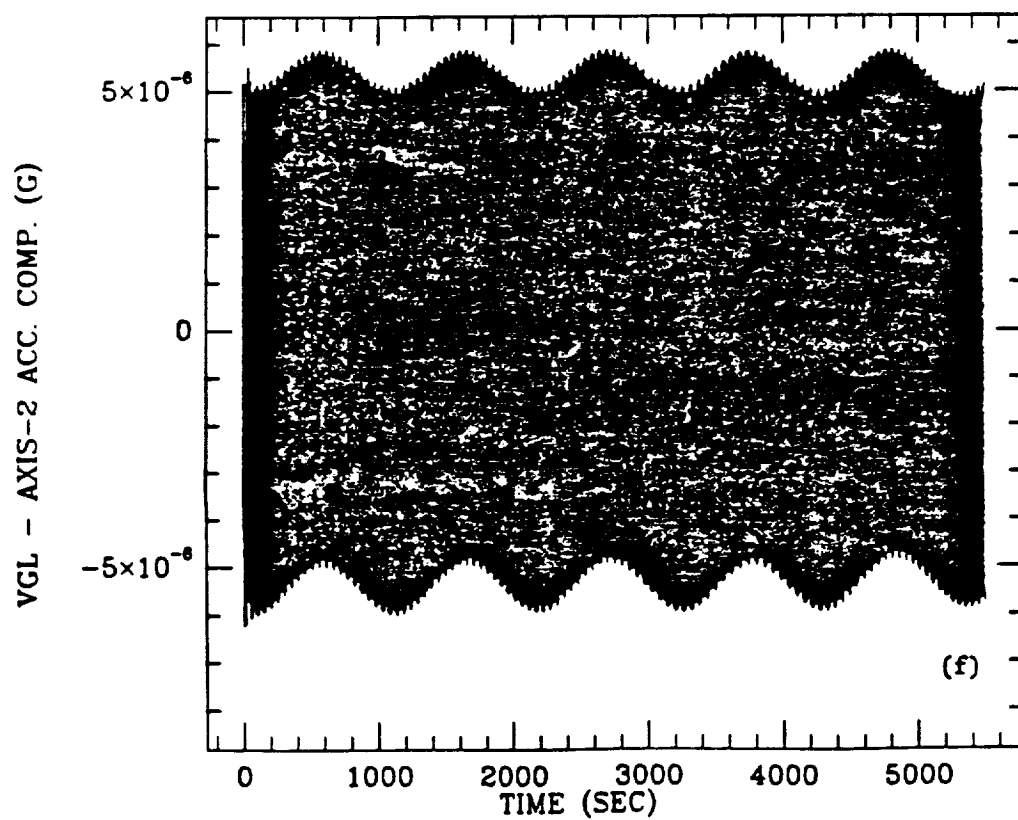
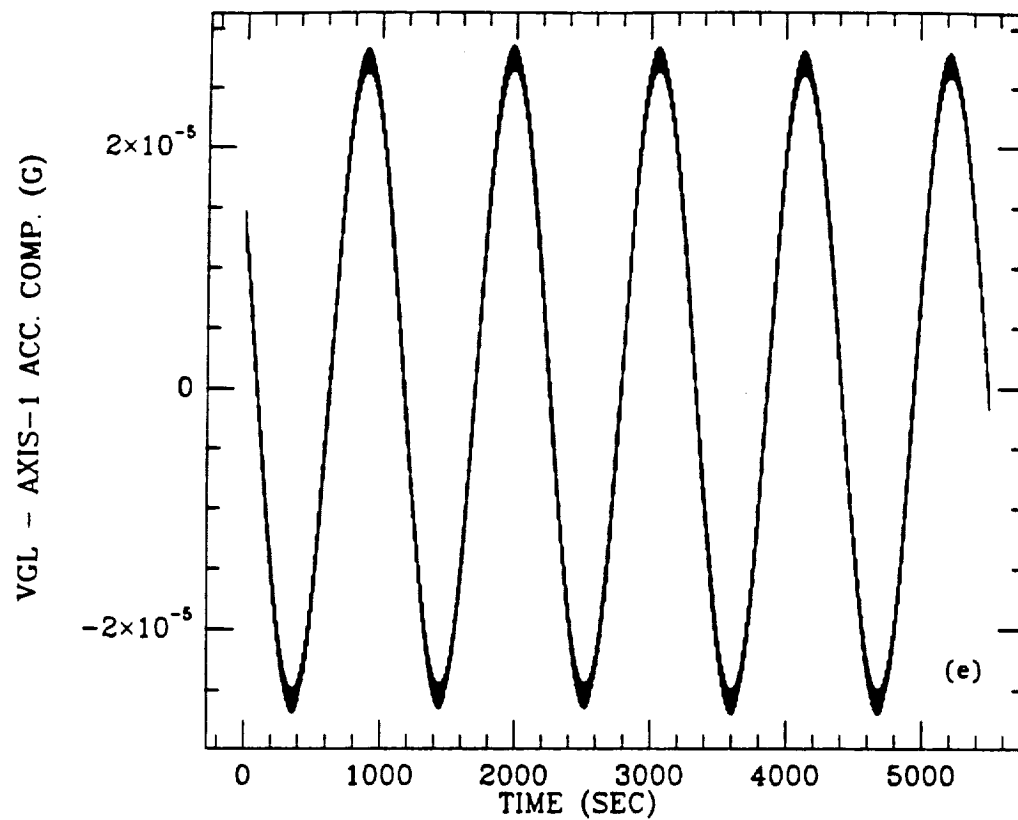


PITCH ANGLE (DEG)



Figures 3.15(a)-(b)

**Figures 3.15(c)-(d)**

**Figures 3.15(e)-(f)**

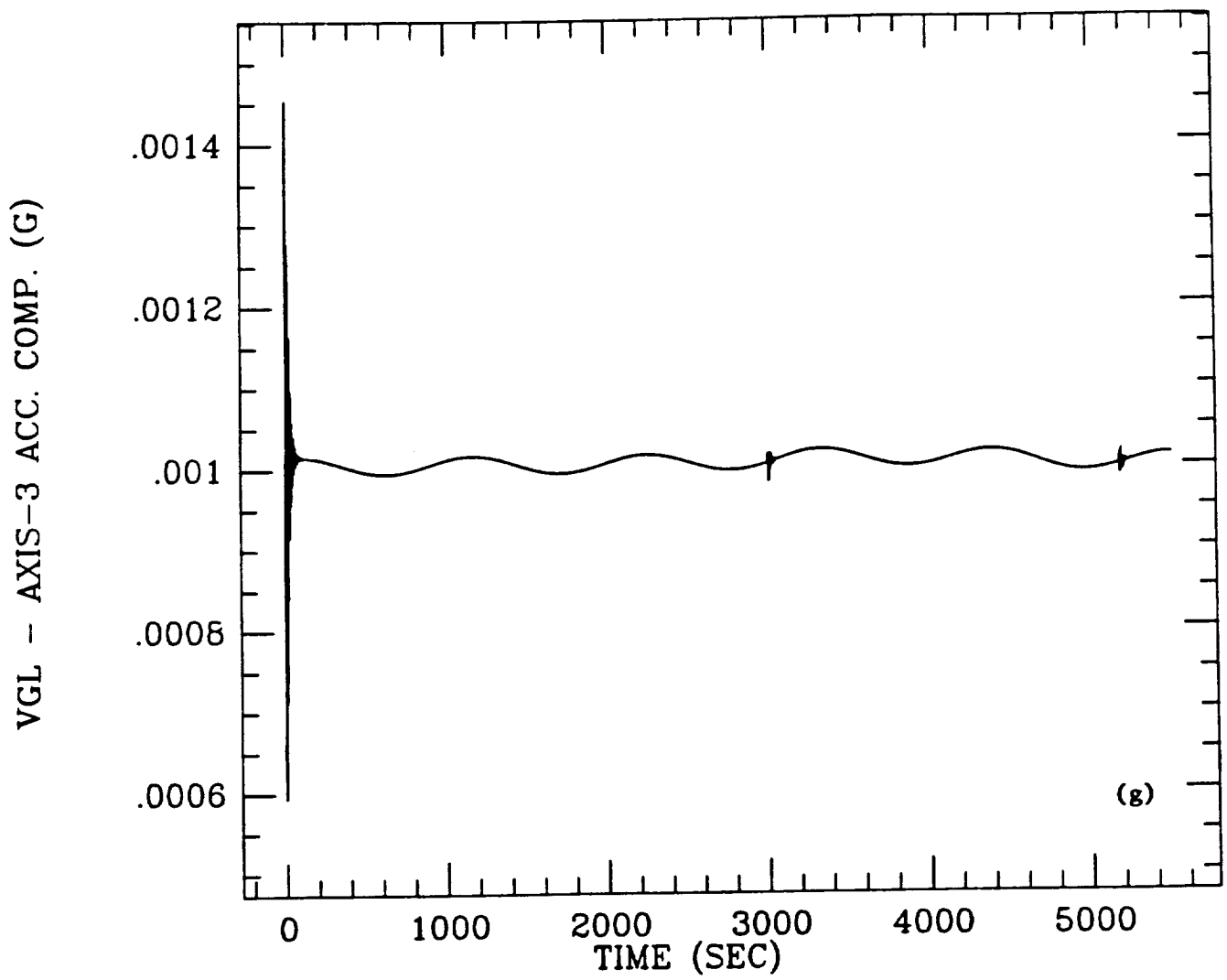
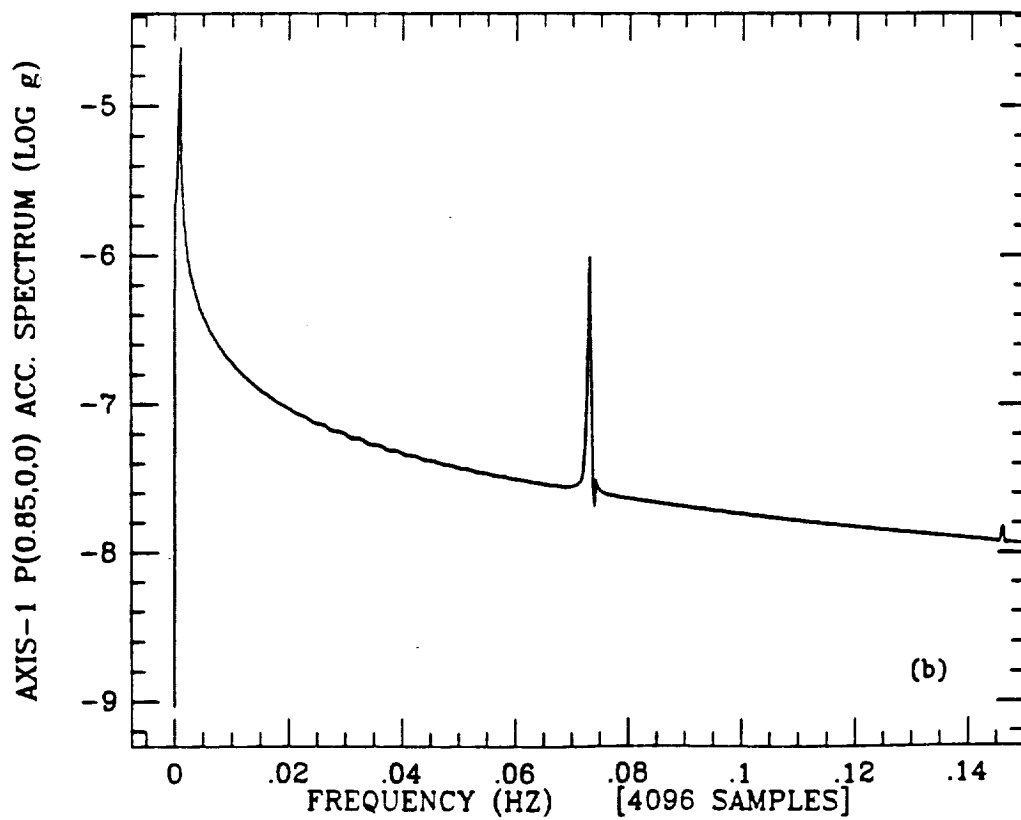
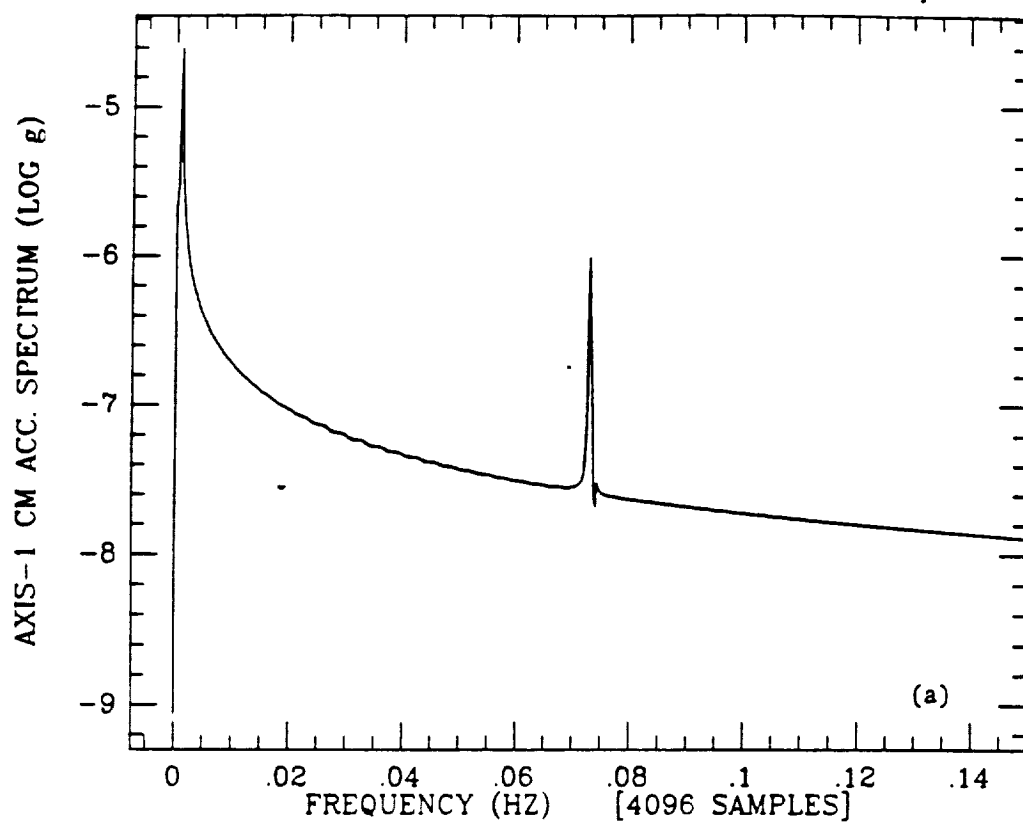
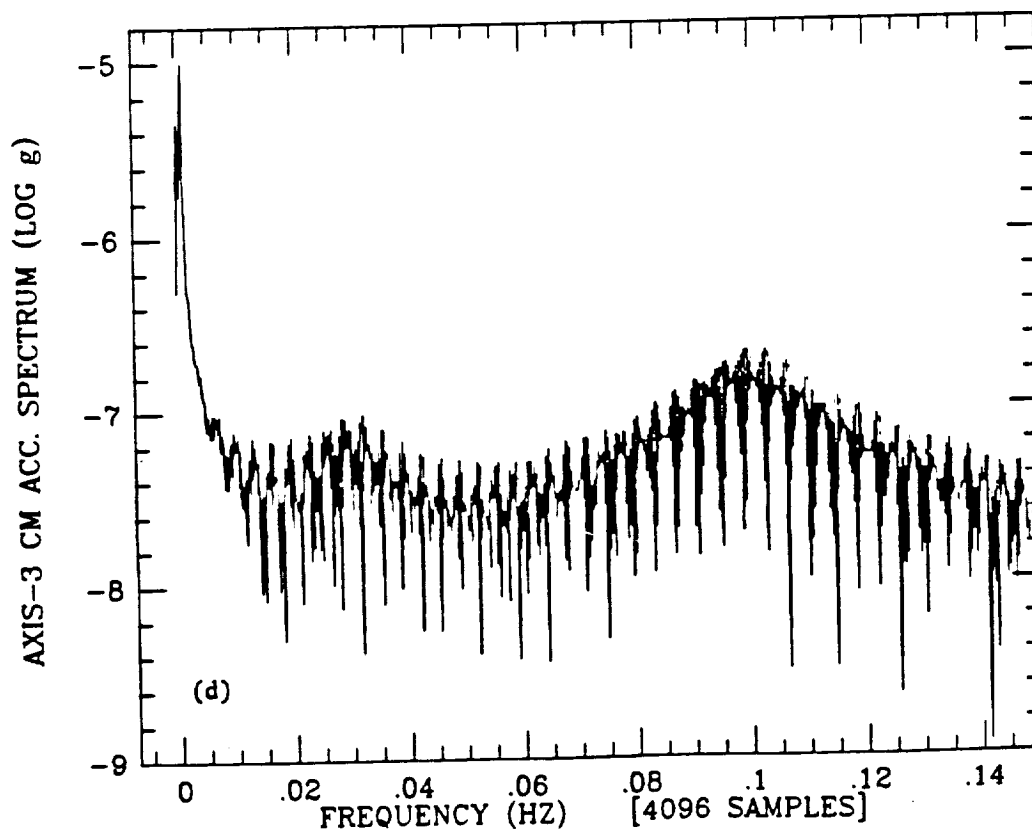
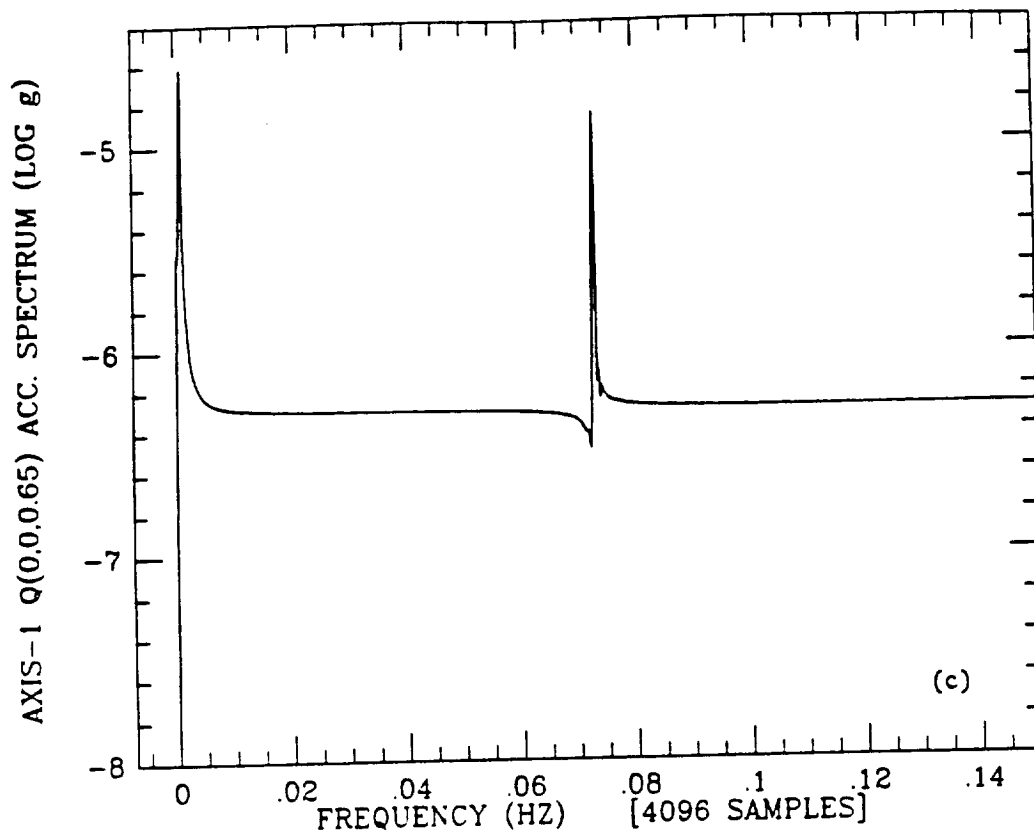
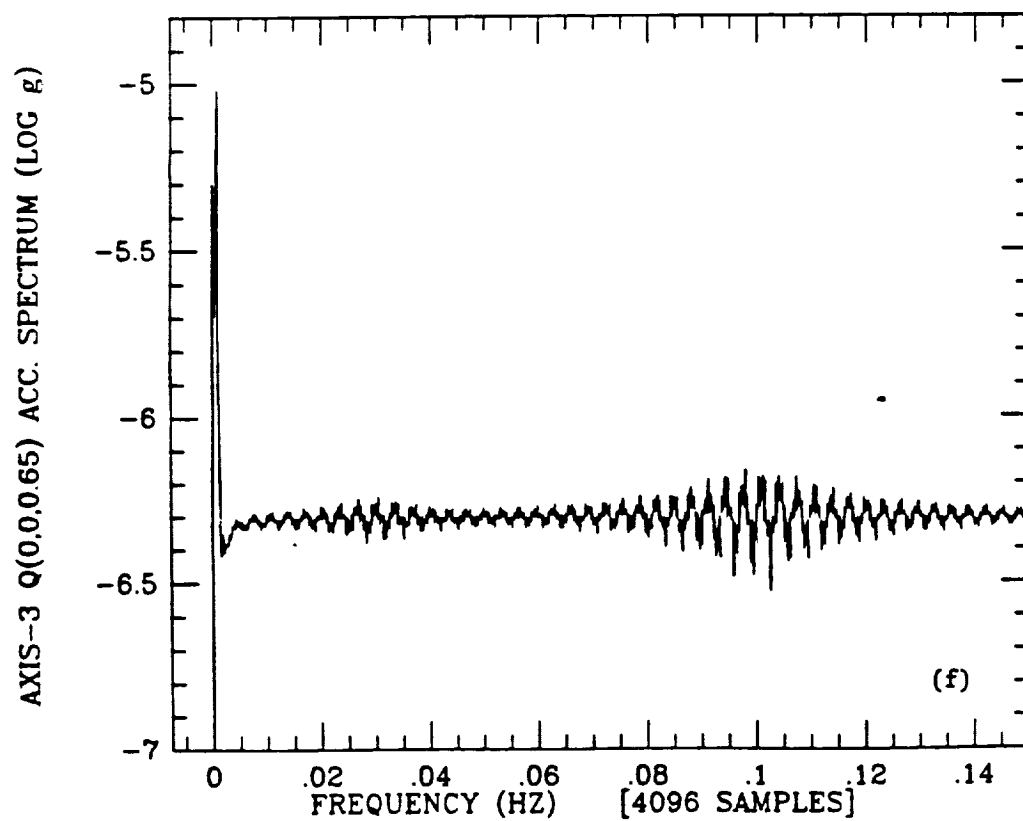
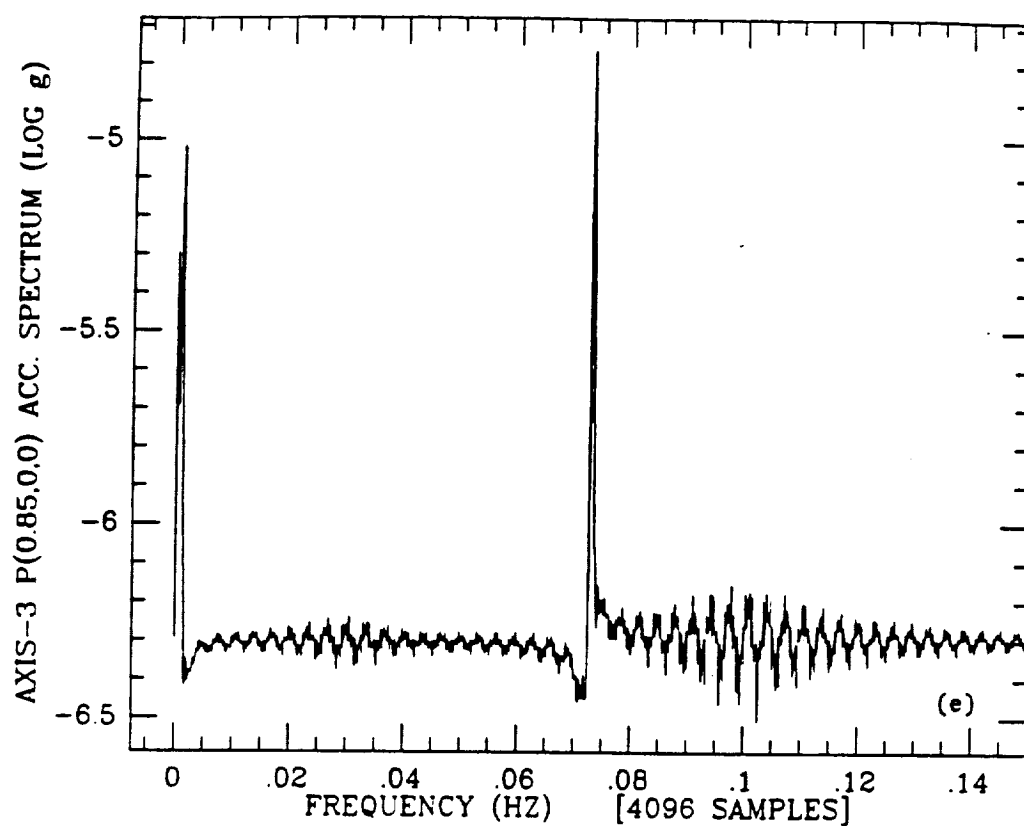


Figure 3.15(g)

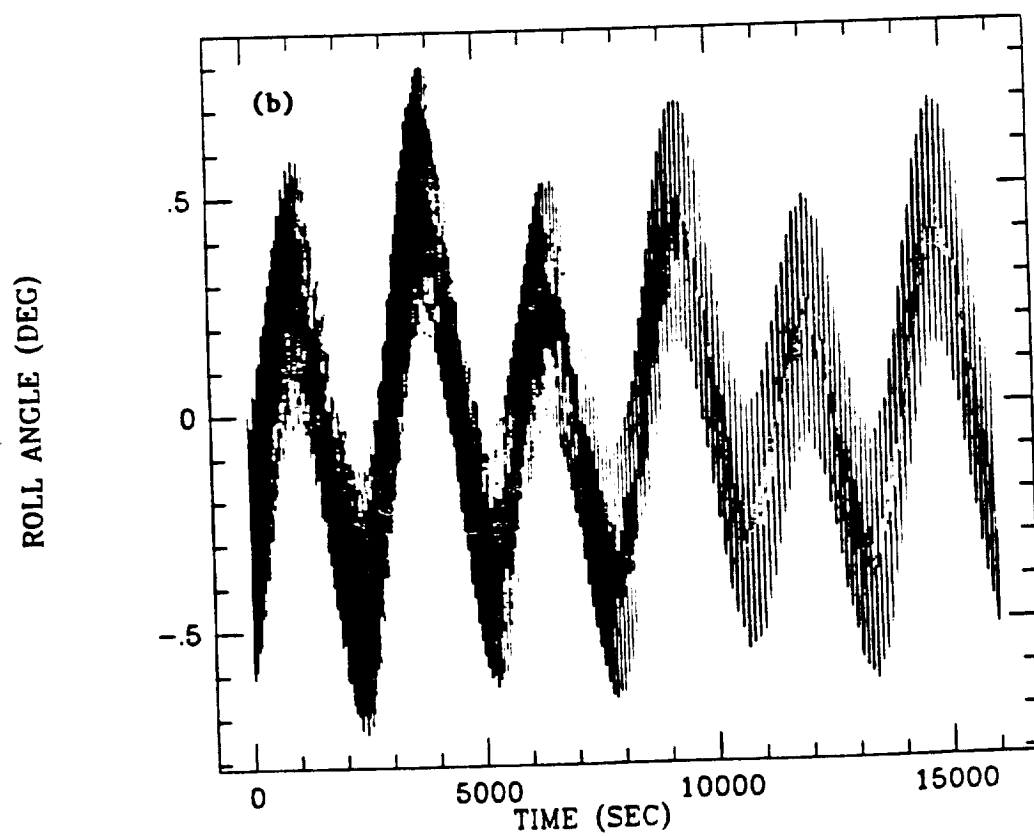
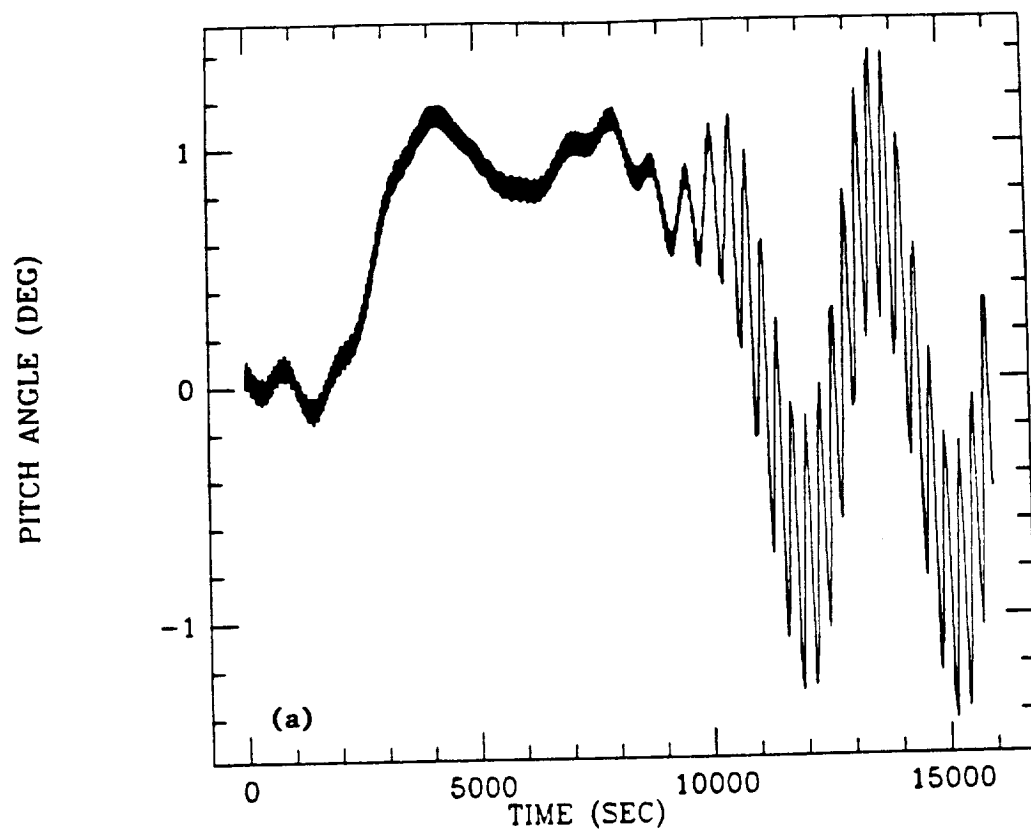
**Figures 3.16(a)-(b)**

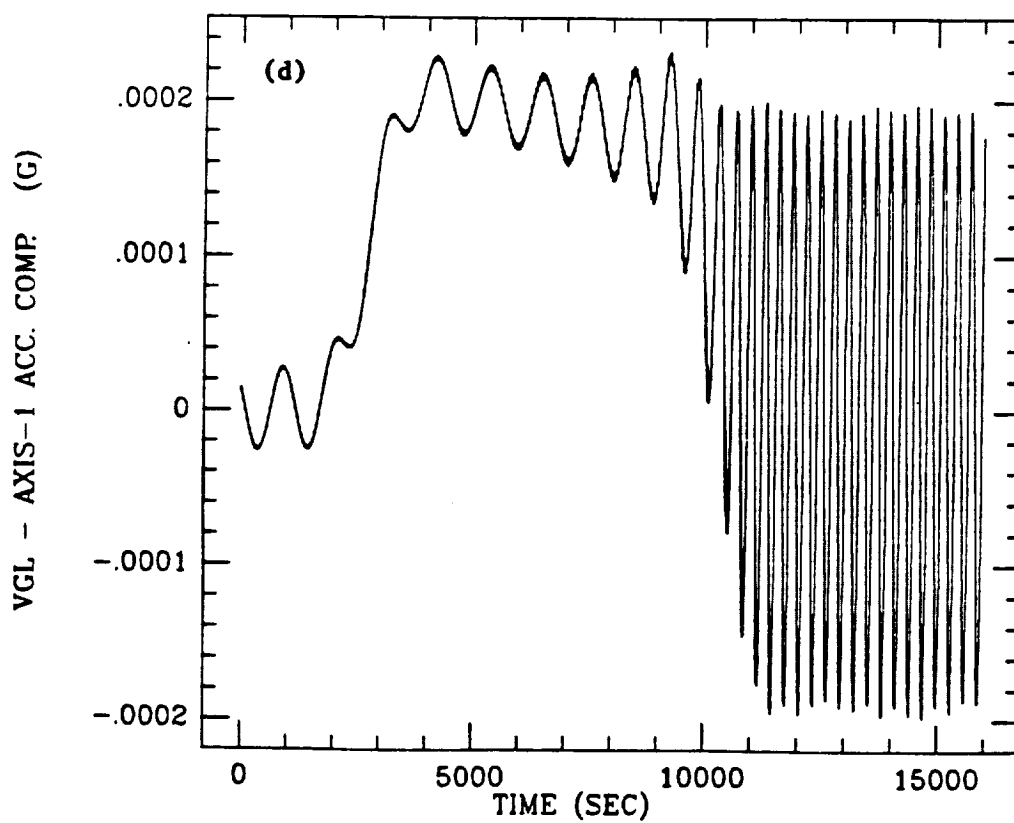
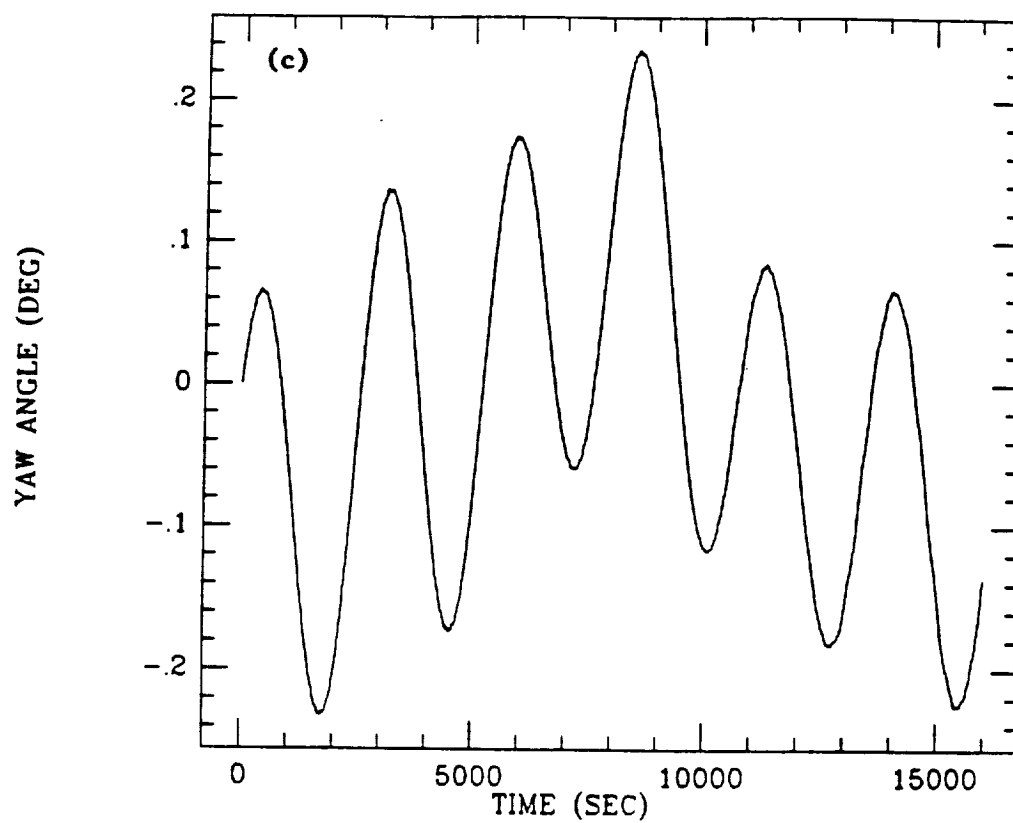


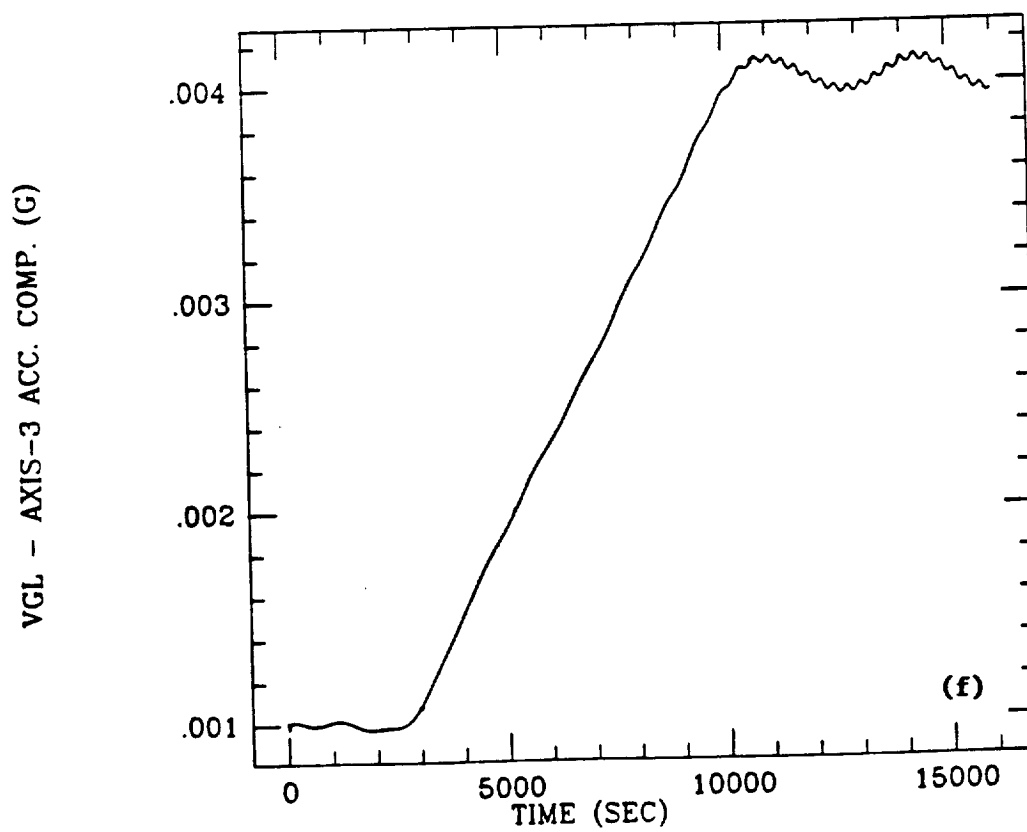
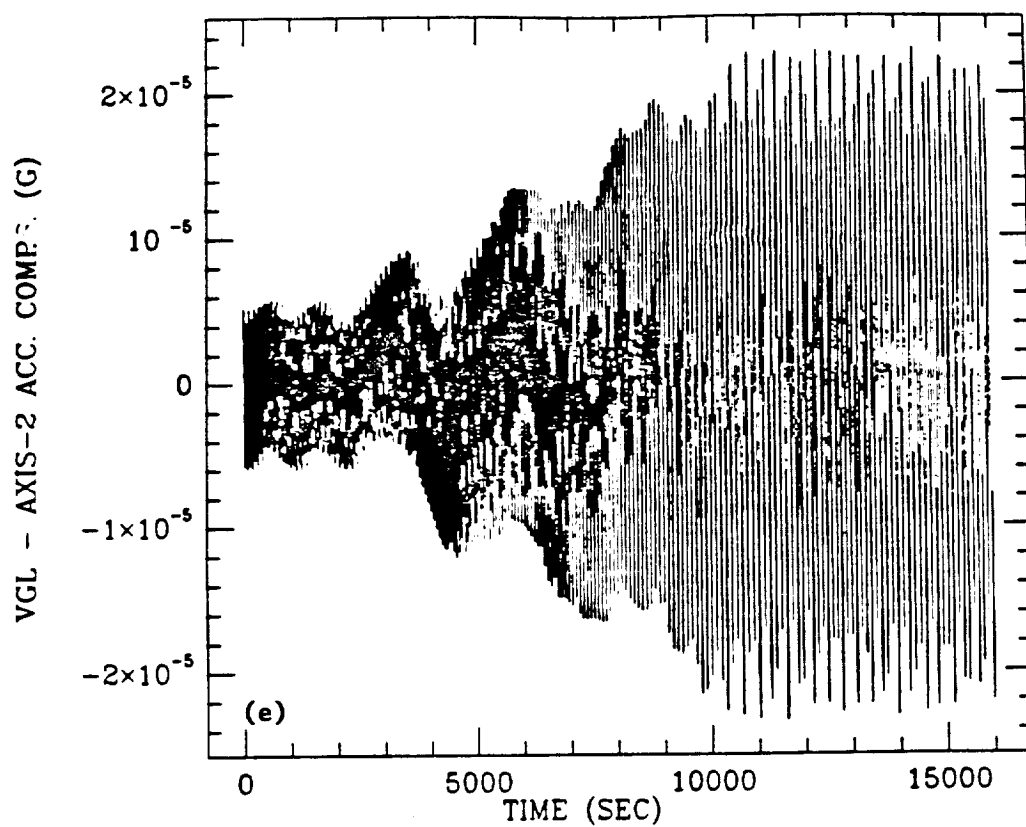
Figures 3.16(c)-(d)



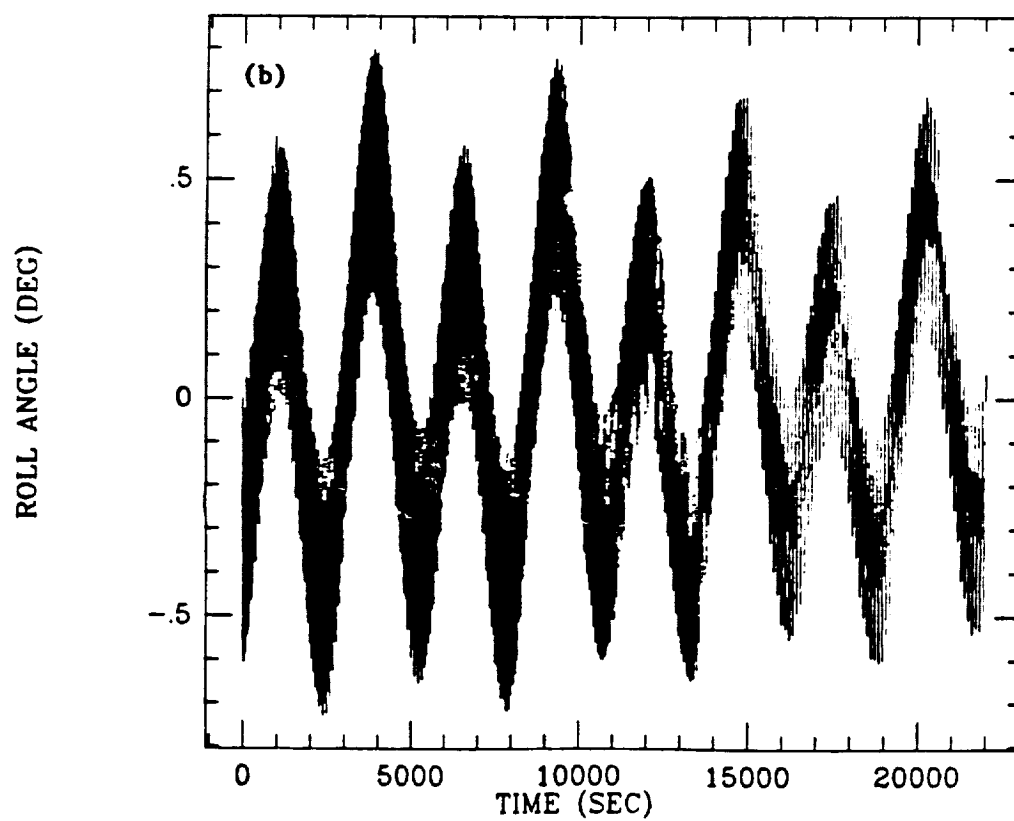
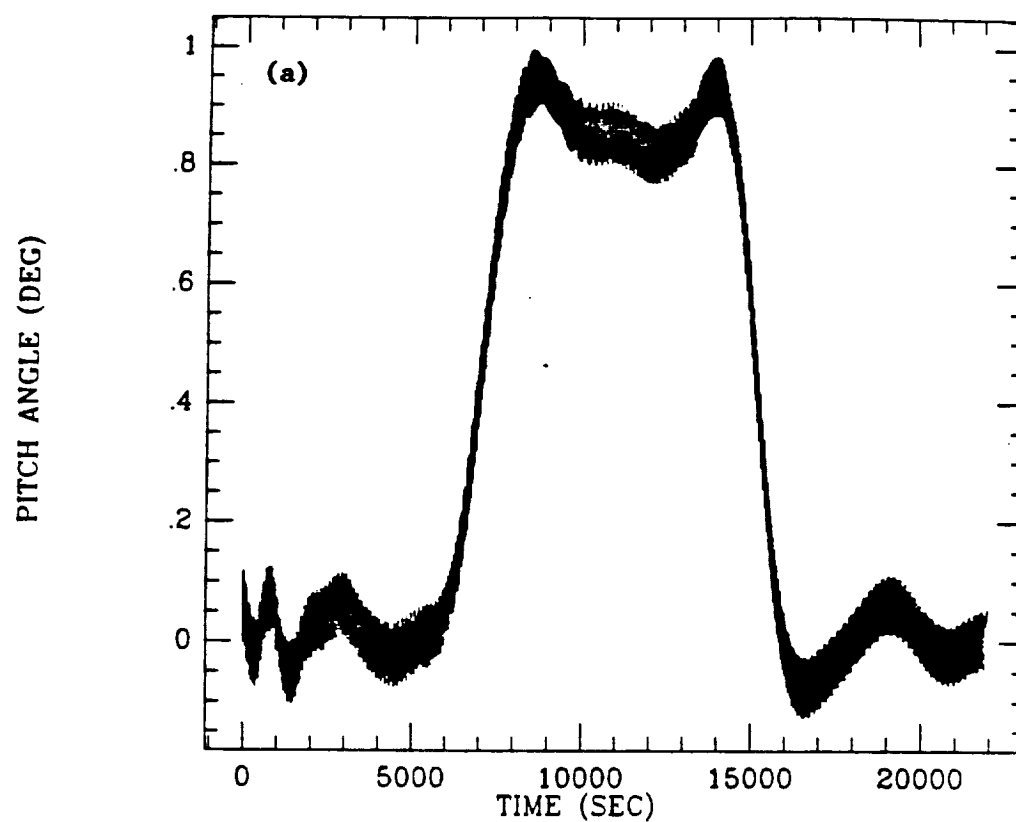
Figures 3.16(e)-(f)

**Figures 3.17(a)-(b)**

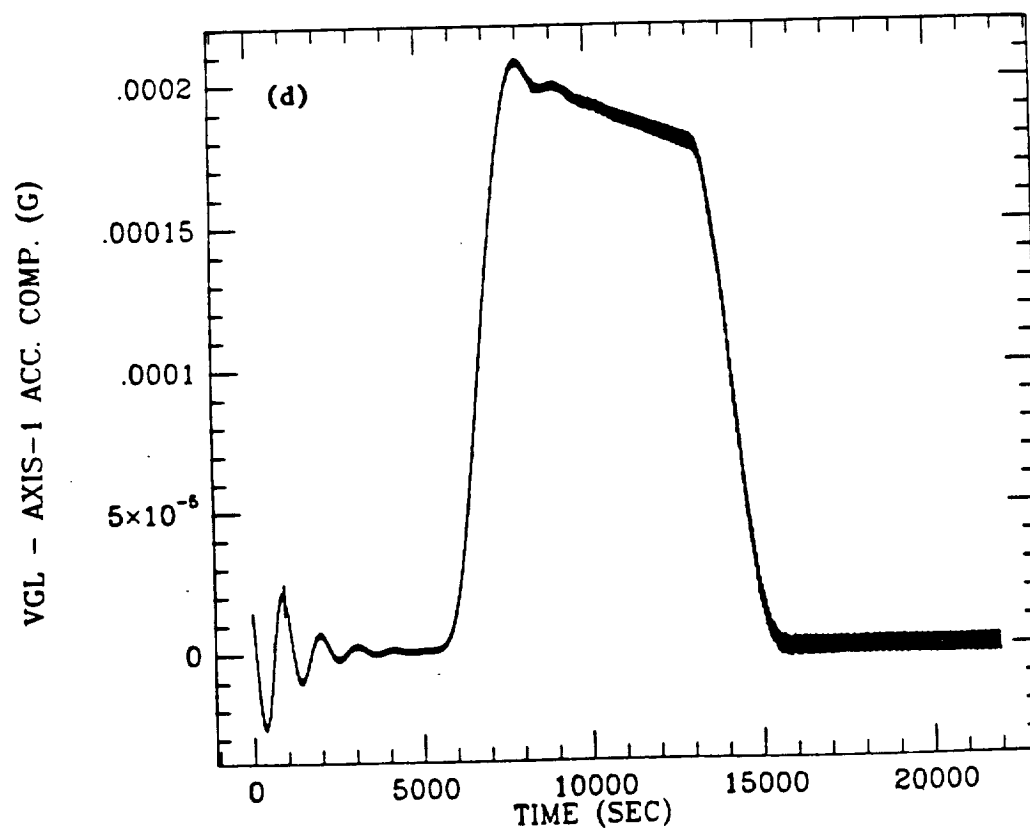
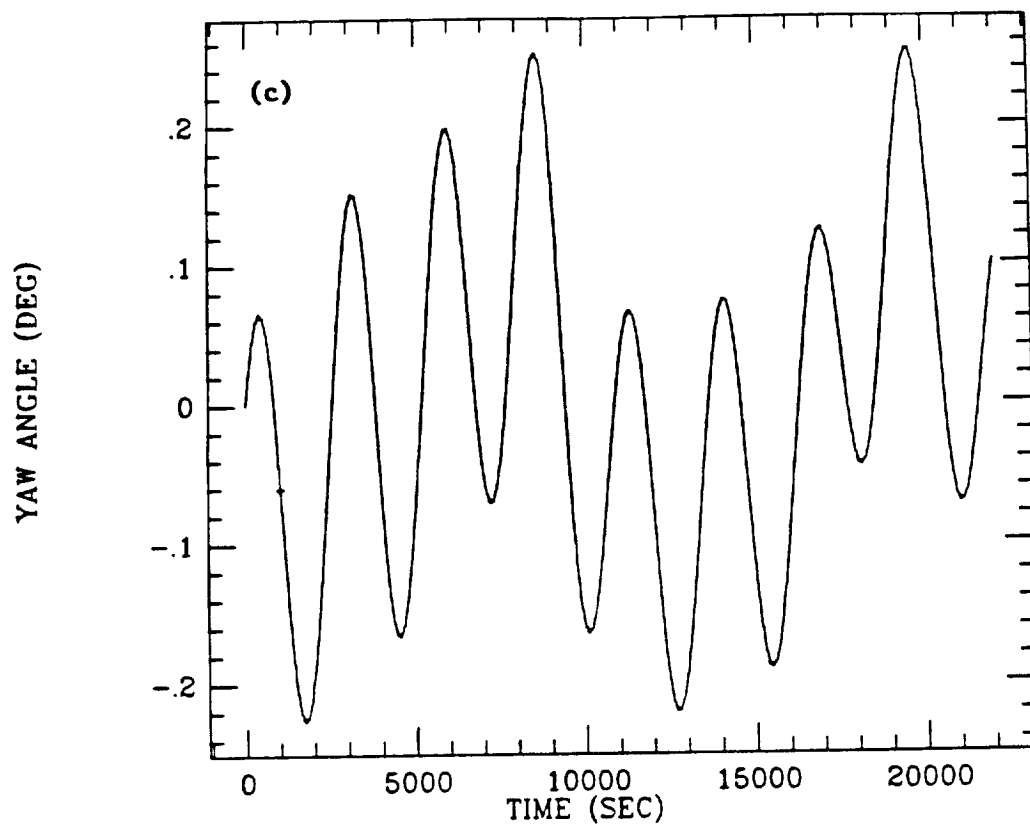
**Figures 3.17(c)-(d)**



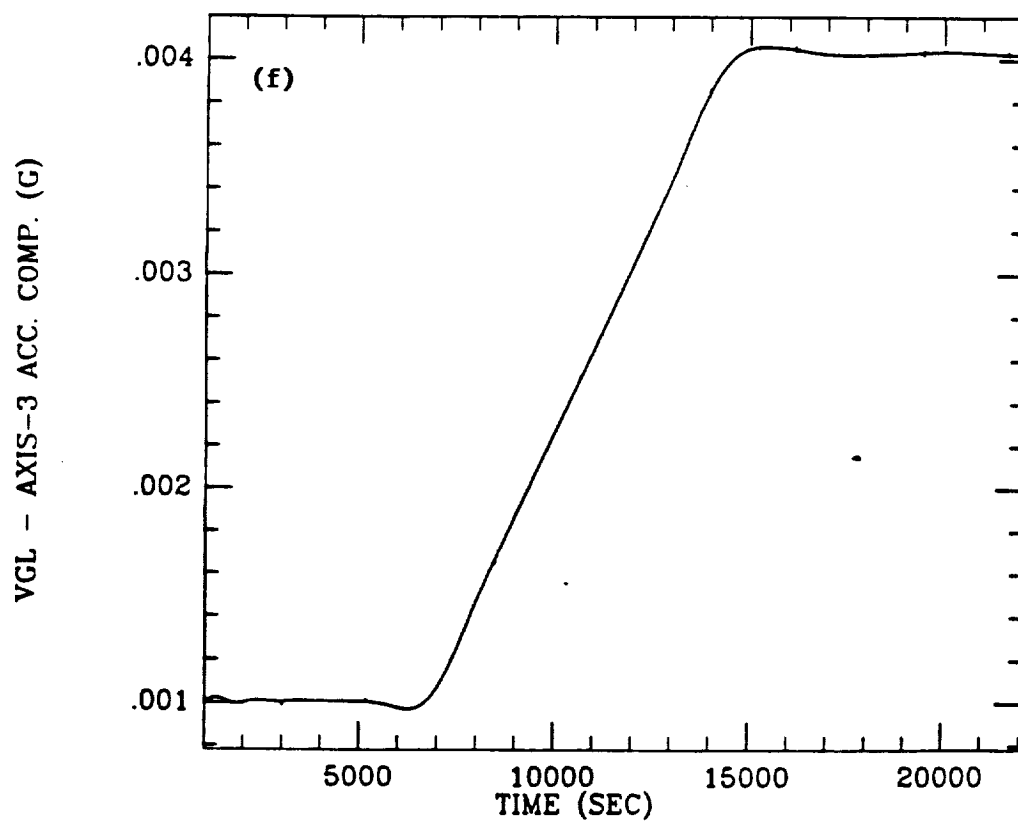
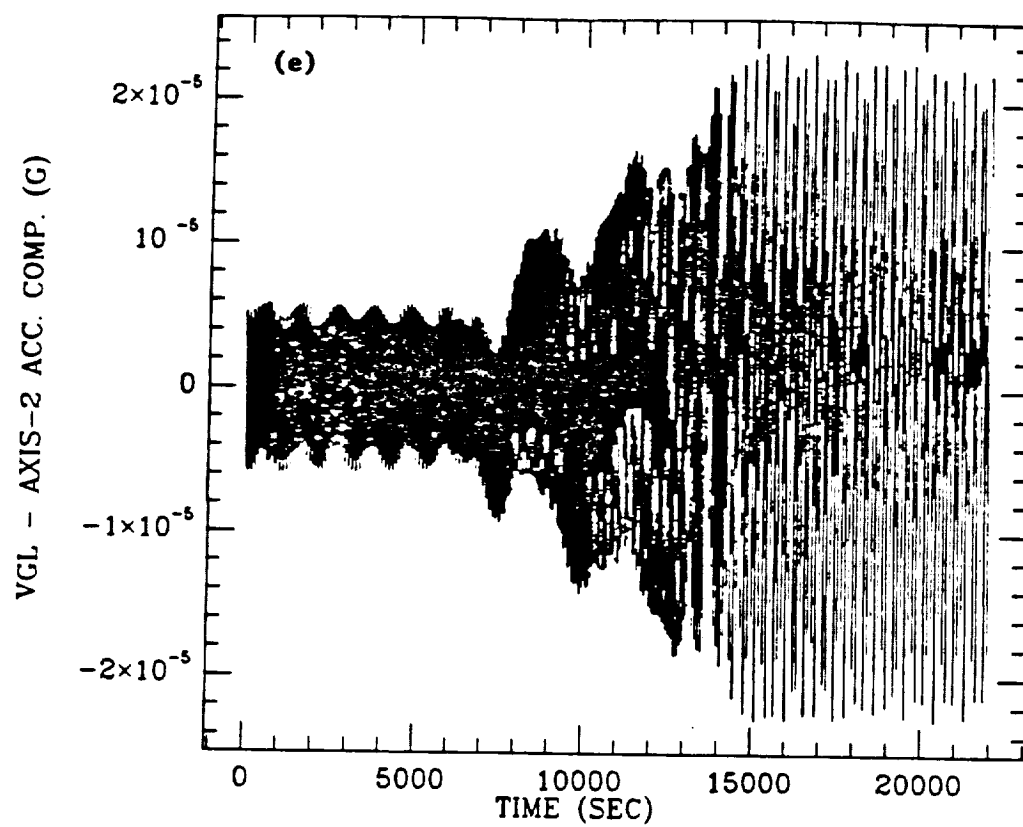
Figures 3.17(e)-(f)



Figures 3.18(a)-(b)



Figures 3.18(c)-(d)



Figures 3.18(e)-(f)

4. TETHER STABILIZER FOR SPACE STATION ATTITUDE

4.1 Introductory Remarks

In the following the performance of a tethered system for controlling the Space Station (SS) attitude in the event of a failure or malfunction of the Station attitude control system (ACS) is investigated.

The present SS configuration has problems of attitude stability because of its mass and geometrical asymmetry. The torque equilibrium angle of the SS is around 16° [1] which is unusually high. Moreover, the load on the ACS is heavy during the flight in order to provide the desired attitude orientation of the SS.

From a previous analysis [2] a tether system show promises for controlling the SS attitude around the three axes, in the absence of any other attitude control system.

4.2 Space Station Model

The mass and orbital characteristics for the SS are as follows [1]:

Mass	219000 kg	
Orbital Altitude	352 Km	
Orbital Inclination	28.5°	
Drag Area	2169 m ²	
Moments of Inertia (kg-m ²)		
I _{xx} = 9.08x10 ⁷	I _{yy} = 2.54x10 ⁷	I _{zz} = 1.05x10 ⁸
I _{xy} = 1.12x10 ⁶	I _{xz} = -1.62x10 ⁶	I _{yz} = -5.52x10 ⁵
Center of Gravity (CG) Location with respect to Truss Center (m)		

$$X_{CG} = -3.16 \quad Y_{CG} = 0 \quad Z_{CG} = 3.36$$

Center of Pressure (CP) Location with respect to CG (m)

$$X_{CP} = 0 \quad Y_{CP} = -0.3 \quad Z_{CP} = -3.5$$

Where the reference frame XYZ has its origin located at the SS CG and its axes are as follows:

Z-axis	along the local vertical toward the Earth;
X-axis	along the local horizontal in the orbital plane (coincides with the velocity vector for a circular orbit);
Y-axis	completes the right-handed reference frame.

This reference frame is called the Local Horizontal-Local Vertical reference frame or alternatively the rotating reference frame. When the SS has the ideal attitude orientation this reference frame coincides with the geometric body reference frame later defined.

Since the SAO computer code integrates the attitude equations in the principal body frame $X_1X_2X_3$, we compute the eigenvalues of the inertia matrix. These eigenvalues are the three principal moments of inertia :

$$J_1 = 9.064 \times 10^7 \text{ kg-m}^2$$

$$J_2 = 2.538 \times 10^7 \text{ kg-m}^2$$

$$J_3 = 1.052 \times 10^8 \text{ kg-m}^2$$

We also define the geometric body reference frame with the origin at the SS CG as follows:

Y_G -axis	along the truss;
-------------	------------------

X_G -axis	perpendicular to the truss toward the velocity vector;
Z_G -axis	completes the right handed reference frame.

The orientation of the principal reference frame with respect to the geometric reference frame is obtained by means of a 3-2-1 rotation sequence, as follows:

- 1st rotation around axis Z_G (yaw axis)
- 2nd rotation around axis Y_G' (pitch axis)
- 3rd rotation around axis X_G'' (roll axis)

The principal reference frame is rotated with respect to the geometric body reference frame by the following angles [1]:

$$\vartheta_1(Z_G) = 1^\circ \qquad \vartheta_2(Y_G') = -6.27^\circ \qquad \vartheta_3(X_G'') = 0.3^\circ$$

Notice that the ϑ_2 angle is quite larger than the other two angles.

As per Aeritalia's directions, we adopted the following values for the tether system (see Fig. 4.1):

Tether Length	6000 m
Tether Diameter	0.008 m
Tether Mass	434 Kg
Ballast Mass	1413 kg
Distance between tether attachment point and SS CG (along Z_G -axis)	10 m

The SS is assumed to be a rigid structure and the attitude equations of motion are integrated in the principal reference frame. Consequently, the Euler's equations have the classical form whereby the products of inertia are equal to zero.

The torques acting on the Station, modelled in our computer code, are the gravity gradient torque, the aerodynamic torque (which is non-zero because CP does not coincide with CG), and the torque produced on the SS by the tether tension. We call the latter "tether torque".

4.3 Linearized Stability Analysis

The linearized equations of rotational motion of the SS tethered to a ballast aligned the local vertical are as follows:

$$\ddot{\theta} + 3\Omega^2 (r d m_E / J_2 + k_2) \theta = 0 \quad (21.1)$$

$$\dot{\phi} - (1 - k_1) \Omega \dot{\psi} + \Omega^2 (3 r d m_E / J_1 + 4 k_1) \phi = 0 \quad (21.2)$$

$$\ddot{\psi} + (1 - k_3) \Omega \dot{\phi} + \Omega^2 k_3 \psi = 0 \quad (21.3)$$

where:

$$k_1 = (J_2 - J_3)/J_1 \quad k_2 = (J_1 - J_3)/J_2 \quad k_3 = (J_2 - J_1)/J_3$$

In eqns (21) Ω is the orbital rate, θ , ϕ and ψ the pitch, roll, and yaw angles respectively, $m_E = m_B + m_T/2$ the equivalent mass, m_B and m_T the ballast and the tether mass respectively, $d = l + r$ where l is the tether length, and r is the distance between the SS CG and the tether attachment point.

The pitch equation is independent (this is true for small angles only) while the roll and yaw equations are coupled.

After Laplace transforming eqns (21.2) and (21.3) for null initial conditions we obtain the following algebraic equations:

$$(s^2 + c_{11}) [\varphi] + c_{13} [\psi] = 0 \quad (22)$$

$$c_{31} [\varphi] + (s^2 + c_{33}) [\psi] = 0$$

By equating to zero the determinant of eqns (22) we obtain the characteristic equation as follows:

$$s^4 + (c_{11} + c_{33} - c_{13} c_{31}) s^2 + c_{11} c_{33} = 0 \quad (23)$$

where

$$\begin{aligned} c_{11} &= \Omega^2 (4k_1 + 3 \frac{rdm_E}{J_1}) \\ c_{33} &= \Omega^2 k_3 \\ c_{13} &= \Omega (1 - k_1) \\ c_{31} &= \Omega (k_3 - 1) \end{aligned} \quad (24)$$

After applying the Routh-Hurwitz criterion to eqn (23) we obtain the stability conditions as follows [2]:

$$b_2 > 0 \quad \text{and} \quad b_1 > 2\sqrt{b_2} \quad (25)$$

where

$$\begin{aligned} b_1 &= 1 + k_1 k_3 + 3(k_1 + \frac{rdm_E}{J_1}) \\ b_2 &= k_1 k_3 + 3(k_1 + \frac{rdm_E}{J_1}) k_3 \end{aligned}$$

For $k_3 < 0$ (i.e. for the current Station design) and after defining $\tau = drm_E/J_1$, eqns (25) yield

$$\tau < -\frac{4}{3}k_1; \quad \tau < \tau_1; \quad \text{and} \quad \tau > \tau_2 \quad (26)$$

where

$$\tau_1 = -f - \sqrt{\Delta}; \quad \tau_2 = -f + \sqrt{\Delta} \quad (27)$$

and

$$\Delta = f^2 - g$$

$$f = \frac{1}{3}(1 + k_1 k_3 + 3k_1 - 2k_3)$$

$$g = \frac{1}{9}[(1 + k_1 k_3 + 3k_1)^2 - 16k_1 k_3]$$

From eqn (21.1) the pitch motion is stable if

$$\text{dr}m_E > J_3 - J_1 \quad \text{or} \quad \tau > J_3/J_1 - 1 \quad (28)$$

For the current SS design

$$k_1 = -0.88; \quad k_2 = -0.57; \quad k_3 = -0.62 \quad (29)$$

and the stability conditions, given by eqns (26), for the roll-yaw motion yield

$$0.87 < \tau < 1.17 \quad (30)$$

while for the stability of the pitch motion we obtain from eqn (28)

$$\tau > 0.16 \quad (31)$$

Since Aeritalia's values for the tethered system are $l = 6$ km and $r = 10$ m, eqns (30) and (31) translate respectively into

$$1314 \text{ kg} < m_E < 1768 \text{ kg} \quad \text{roll-yaw} \quad (32.1)$$

$$m_E > 241 \text{ kg} \quad \text{pitch} \quad (32.2)$$

Consequently, the value of $m_E = 1630$ kg, selected by Aeritalia, satisfy eqns (32) and we should expect a stable attitude motion of the SS around the three axes at least for small angles.

4.4 Steady-State Dynamic Response

4.4.1 Small Initial Attitude Angles

In the following simulation we assume that the principal reference frame is rotated with respect to the geometric reference frame by a -6.27° pitch angle. The other smaller angular displacements have been neglected. Furthermore, all the environmental perturbations (i.e. thermal, gravitational, and aerodynamical) modelled in the SAO computer code are acting upon the system.

Figures 4.2(a)-4.2(i) show the dynamic response of the system. note that the plots show as attitude angles the angular displacements of the geometric body frame with respect to the Local Horizontal-Local Vertical reference frame.

Since the three attitude angles are bounded we can conclude that the dynamic response is stable: the tether system is able to stabilize the attitude of the Station around the three axes in spite of the external perturbations. This conclusion is certainly true for small attitude angles.

Figures 4.2(d), 4.2(e), and 4.2(f) show the total torque components acting around each station's body axis.

The accelerations acting at the SS's CG are shown in Figures 4.2(g), 4.2(h), and 4.2(i). Since the tether shifts the system CG, the level of the acceleration component along axis-3 is increased with respect to the baseline level. Notice that these acceleration components are measured at the Station CG and hence the rotational acceleration terms (e.g. centrifugal) are very close to zero because the Station center of rotation almost coincides with the SS CG.

4.4.2 Large Initial Attitude Angles

Another simulation was run with large initial attitude angles, namely:

$$\theta_0 \text{ (pitch)} = \varphi_0 \text{ (roll)} = \psi_0 \text{ (yaw)} = 10^\circ$$

The three attitude angles are shown in Figure 4.3. As it can be seen the tether is no longer able to stabilize the yaw/roll modes within the desired boundaries. Note that even though the initial conditions are not very large, the yaw restoring torque provided by the tether is not strong enough to prevent a 90 deg rotation of the station which aligns its transverse boom with the wind velocity vector. Consequently, unless other ways are found for increasing the coupling between roll and yaw, the present configuration of the tether stabilizer is not effective in stabilizing the station yaw motion for moderate values of the initial yaw angle.

It appears that the tether stabilizer must be supplemented by a yaw control system for reducing the station yaw oscillations during transient phases in order for the tether stabilizer to control the station attitude around the three axes in a realistic situation.

Alternative configurations of the tether stabilizer may be worth exploring in order to find ways for strengthening the coupling between the roll and yaw motion.

4.5 Concluding Remarks

From the analysis conducted thus far on the tether stabilizer we conclude that an appropriately designed tether system is able to control the attitude of the Station around three axes in spite of the environmental perturbations when the initial attitude angles are close to zero.

For moderate initial angular displacements (i.e. ≈ 10 deg) the presently designed tether stabilizer is no longer able to control the yaw motion within the desired boundaries.

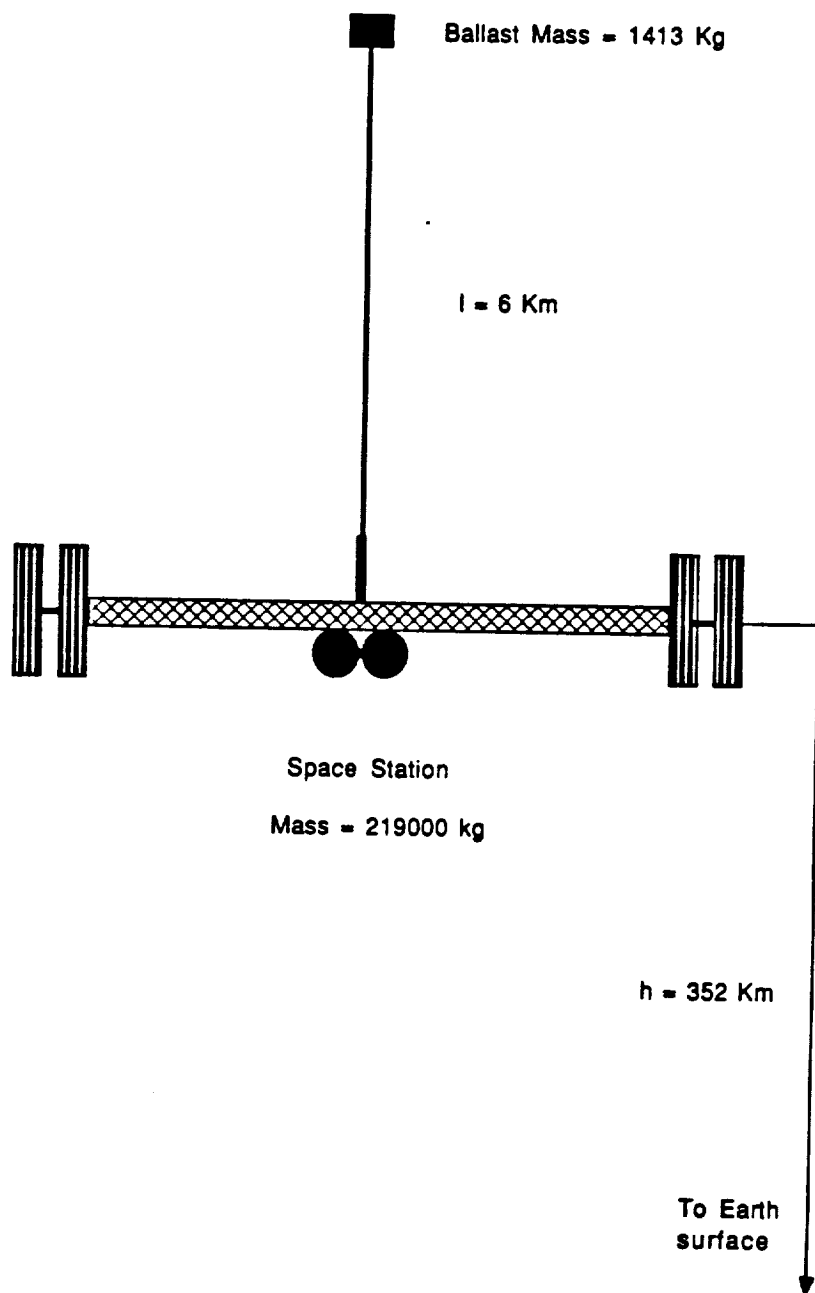
We conclude that the tether stabilizer is effective in controlling the station attitude around the three axes for realistic initial

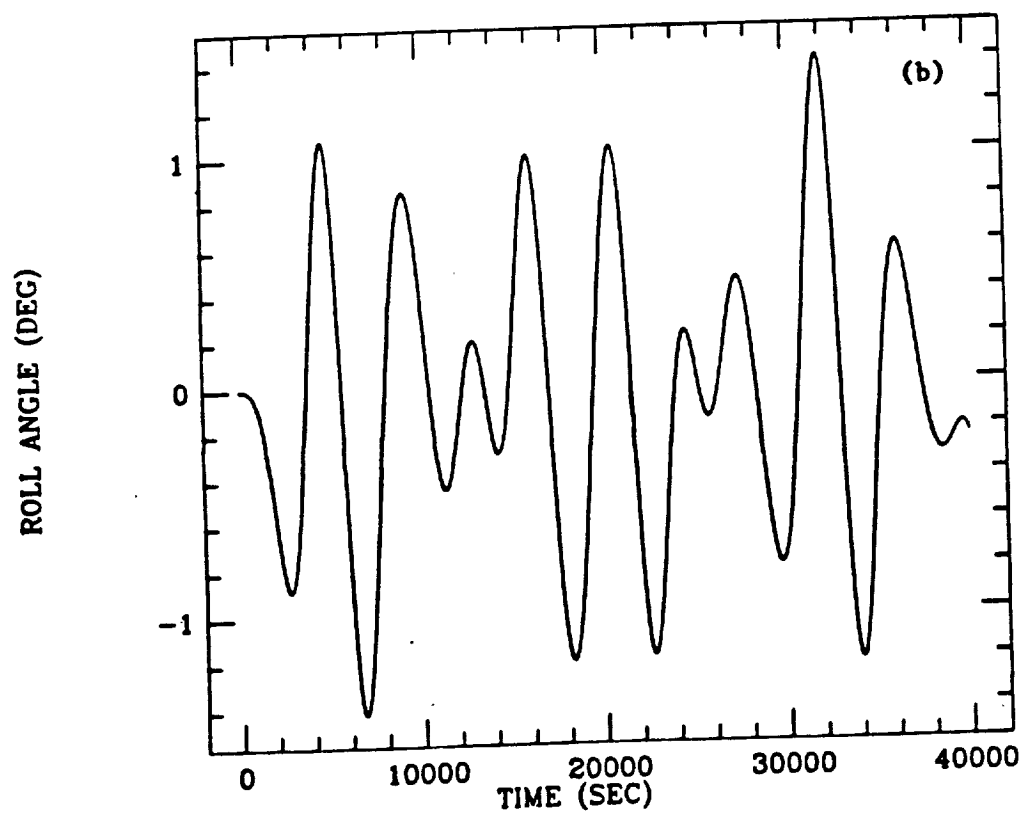
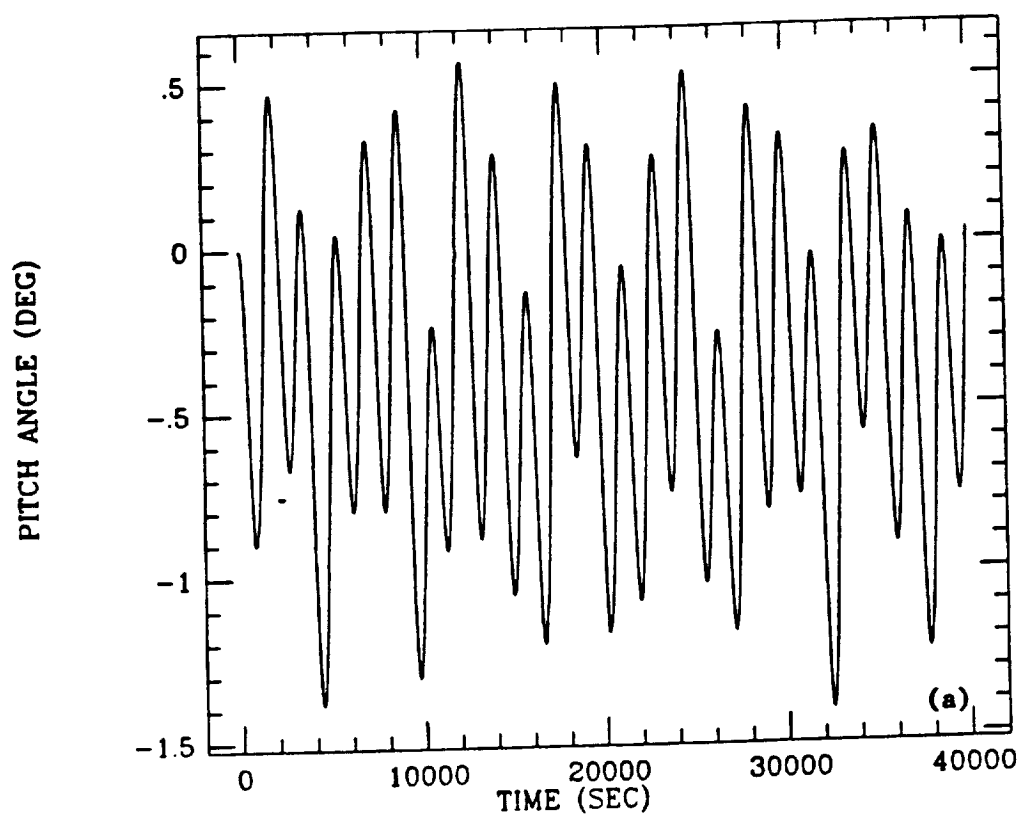
conditions if it is supplemented by an alternative system for controlling the yaw motion during transient phases.

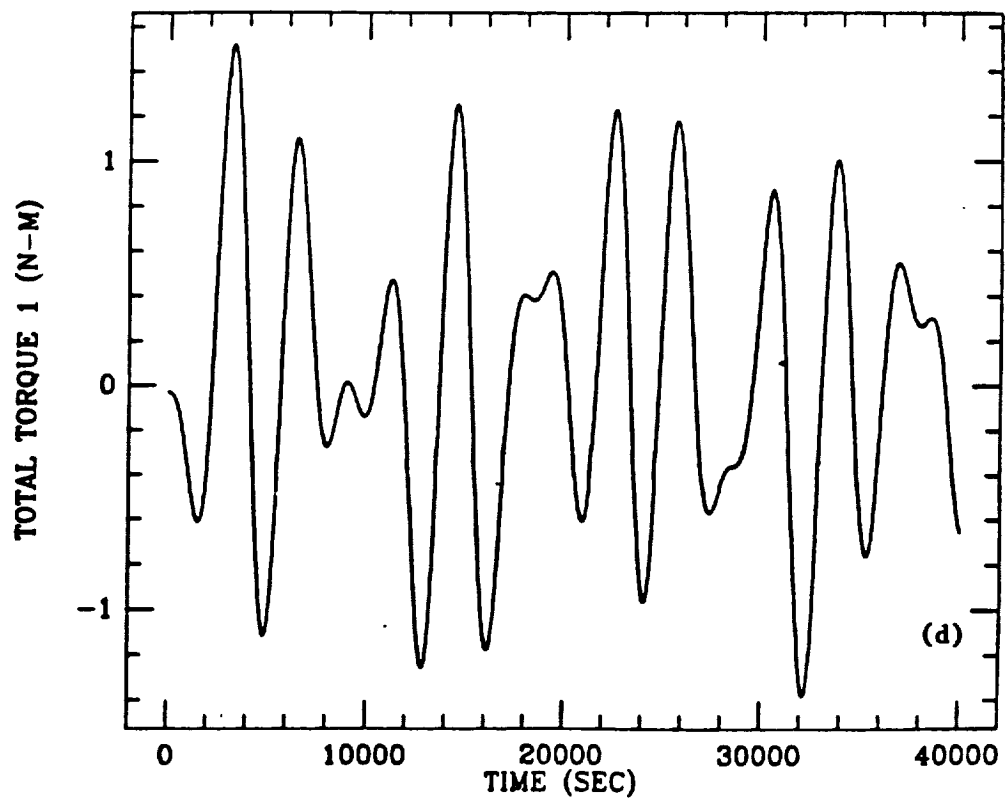
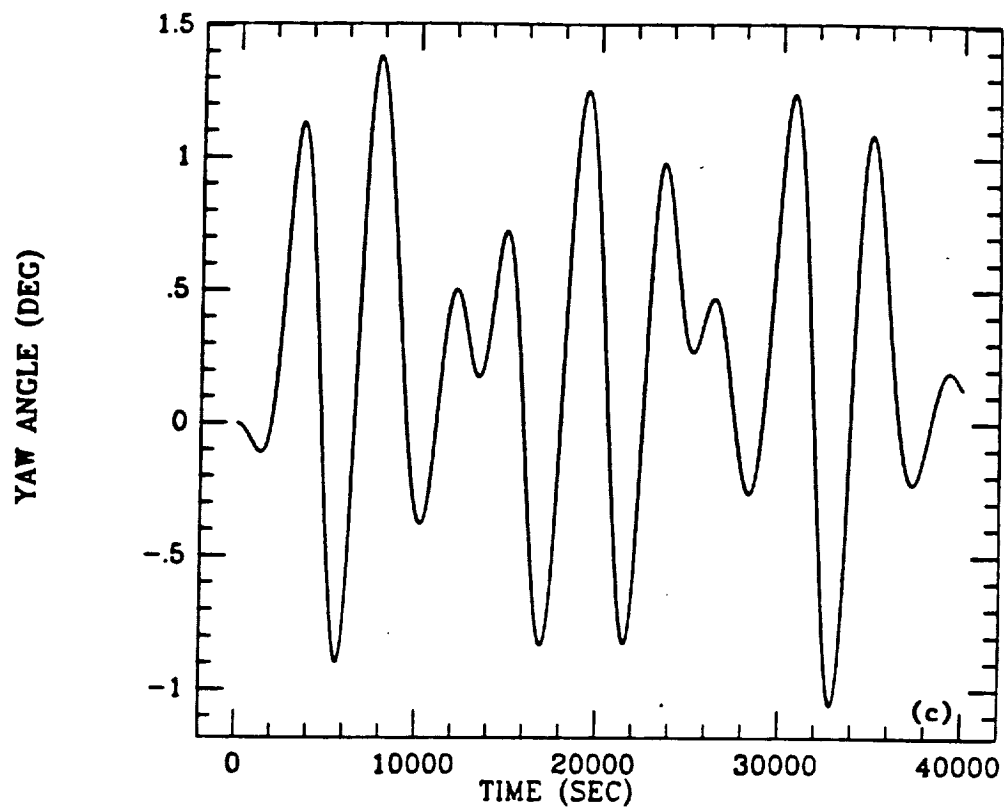
Alternative ways to strengthen the roll/yaw coupling of the tether system may be worth further investigation.

4.6 References to Section 4

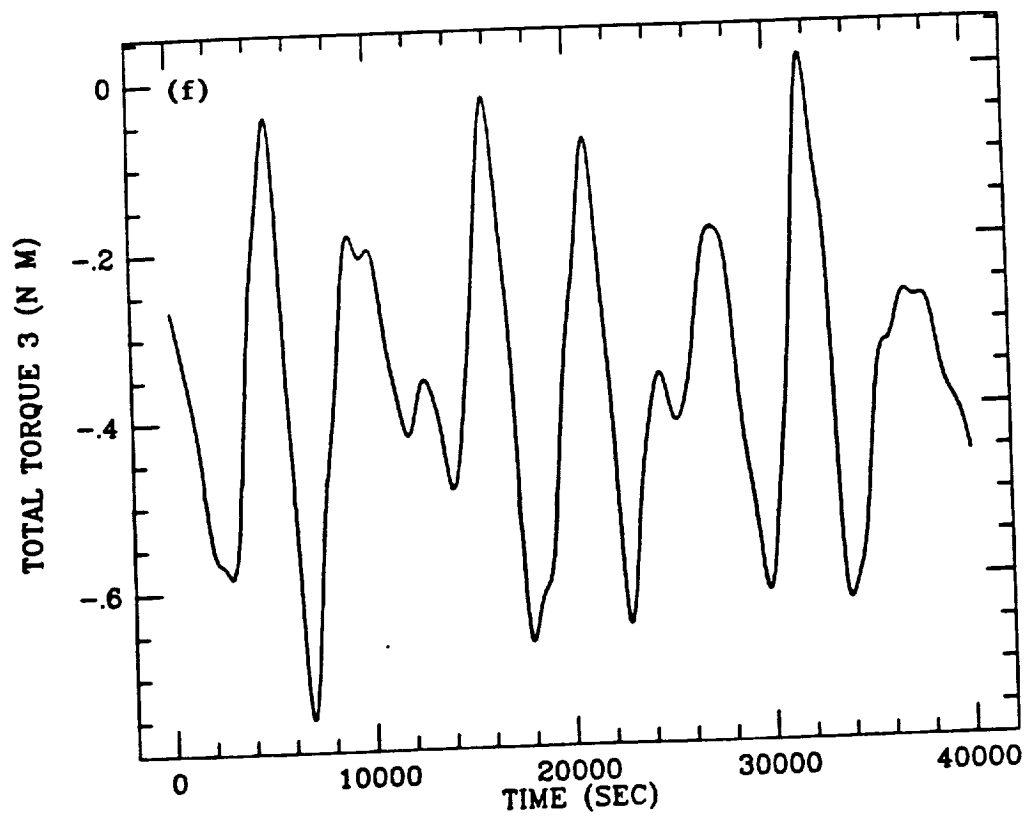
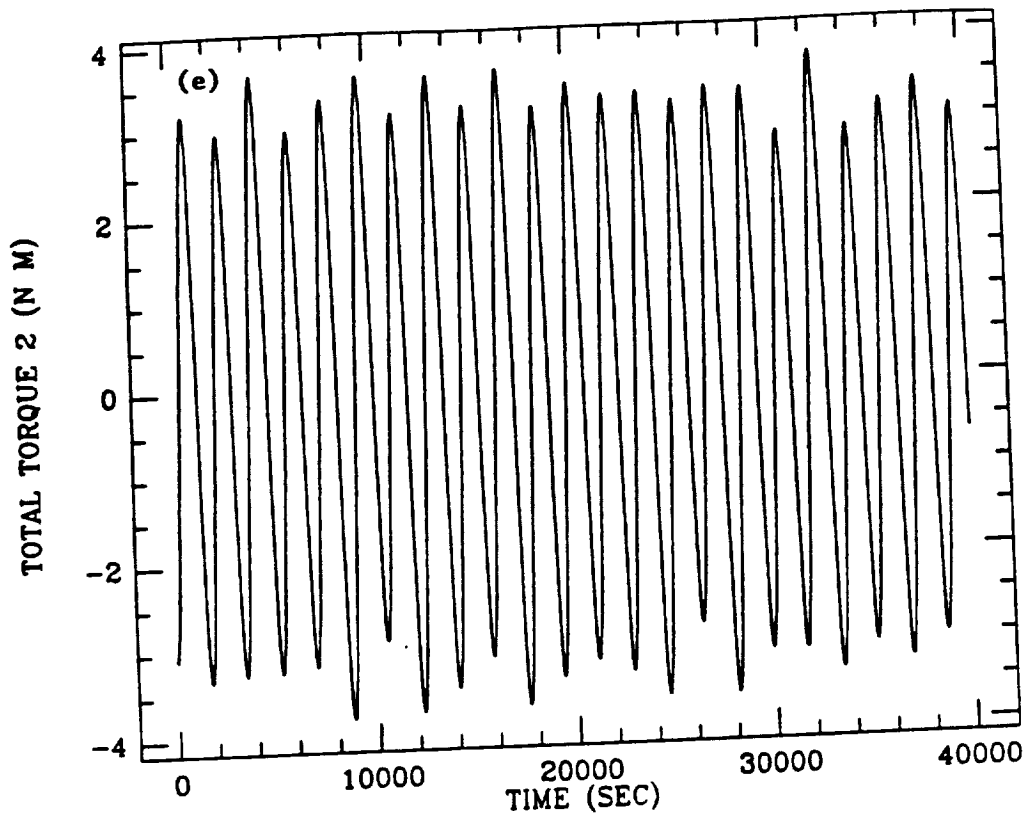
- [1] L. DeRyder, P. Trautman and H. Heck, "The Impact of Asymmetric Physical Properties on Large Space Structures," Proceedings of the AIAA Conference SDM for the International Space Station, Williamsburg, VA, April 21-22, 1988.
- [2] F. Bevilacqua, S. Ciardo and A. Loria, "Space Station Gravity Gradient Stabilization by Tethers," Space Tethers for Science in the Space Station Era, Eds. L. Guerriero and I. Bekey, Societa' Italiana di Fisica, Conference Proceedings, Vol. 14, Bologna, Italy, 1988.

**Figure 4.1**

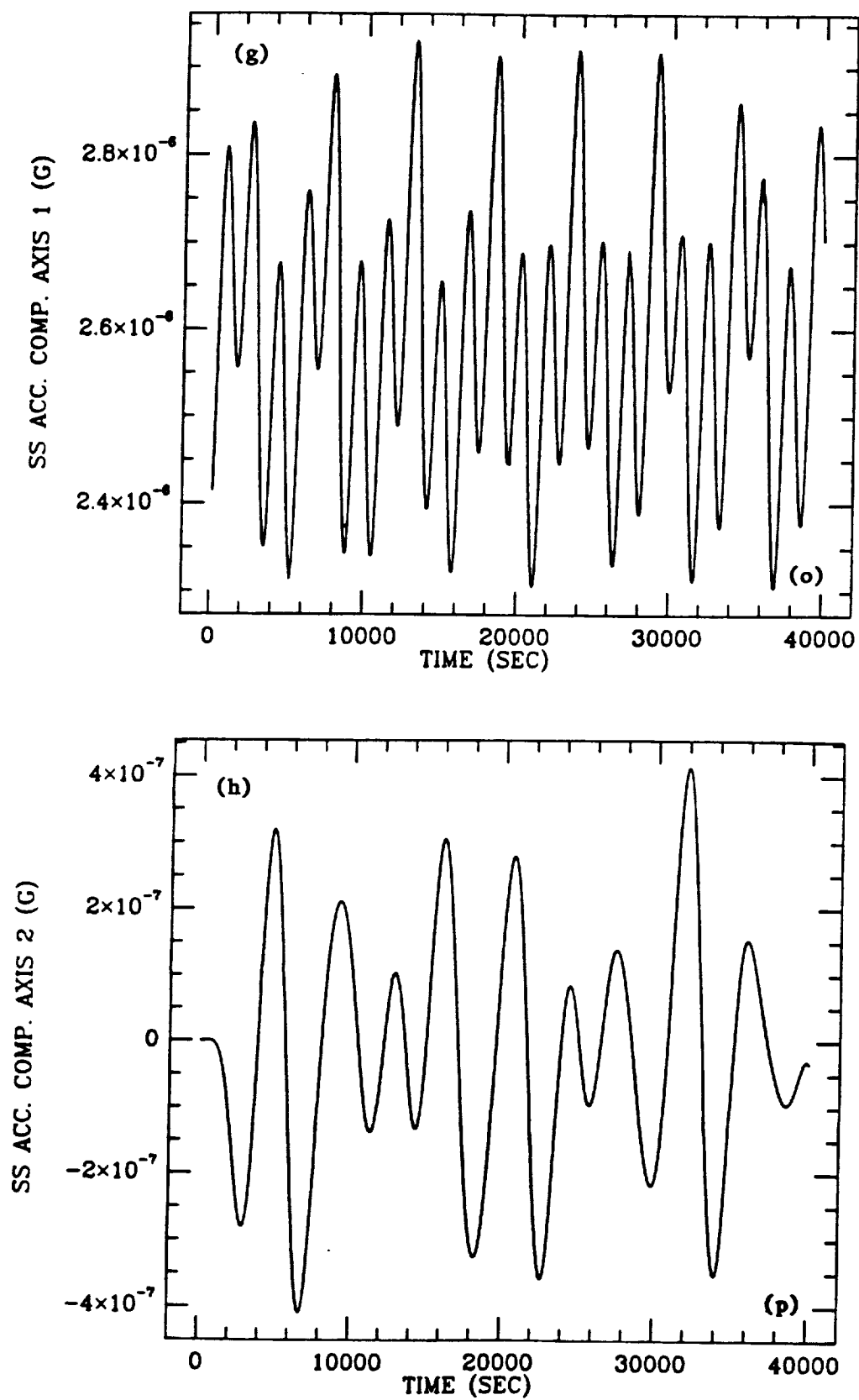
**Figures 4.2(a)-(b)**



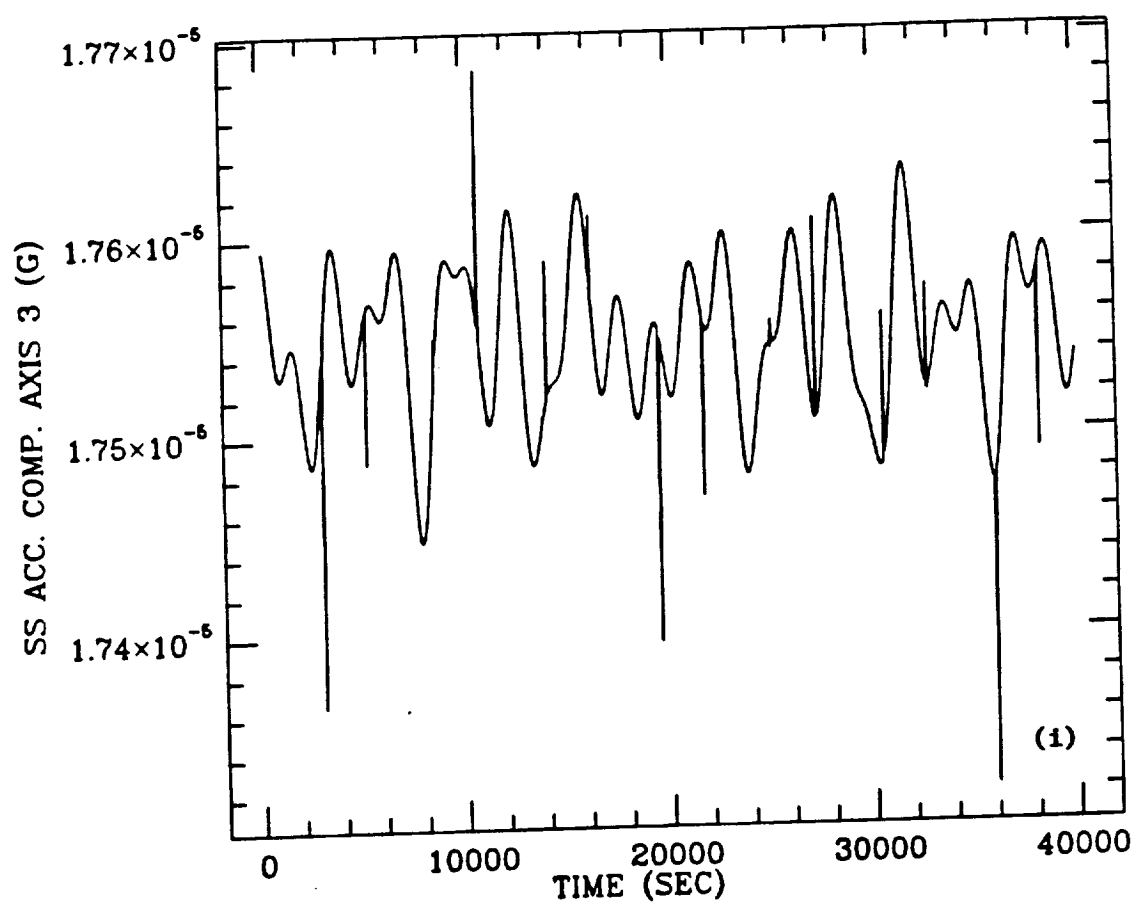
Figures 4.2(c)-(d)

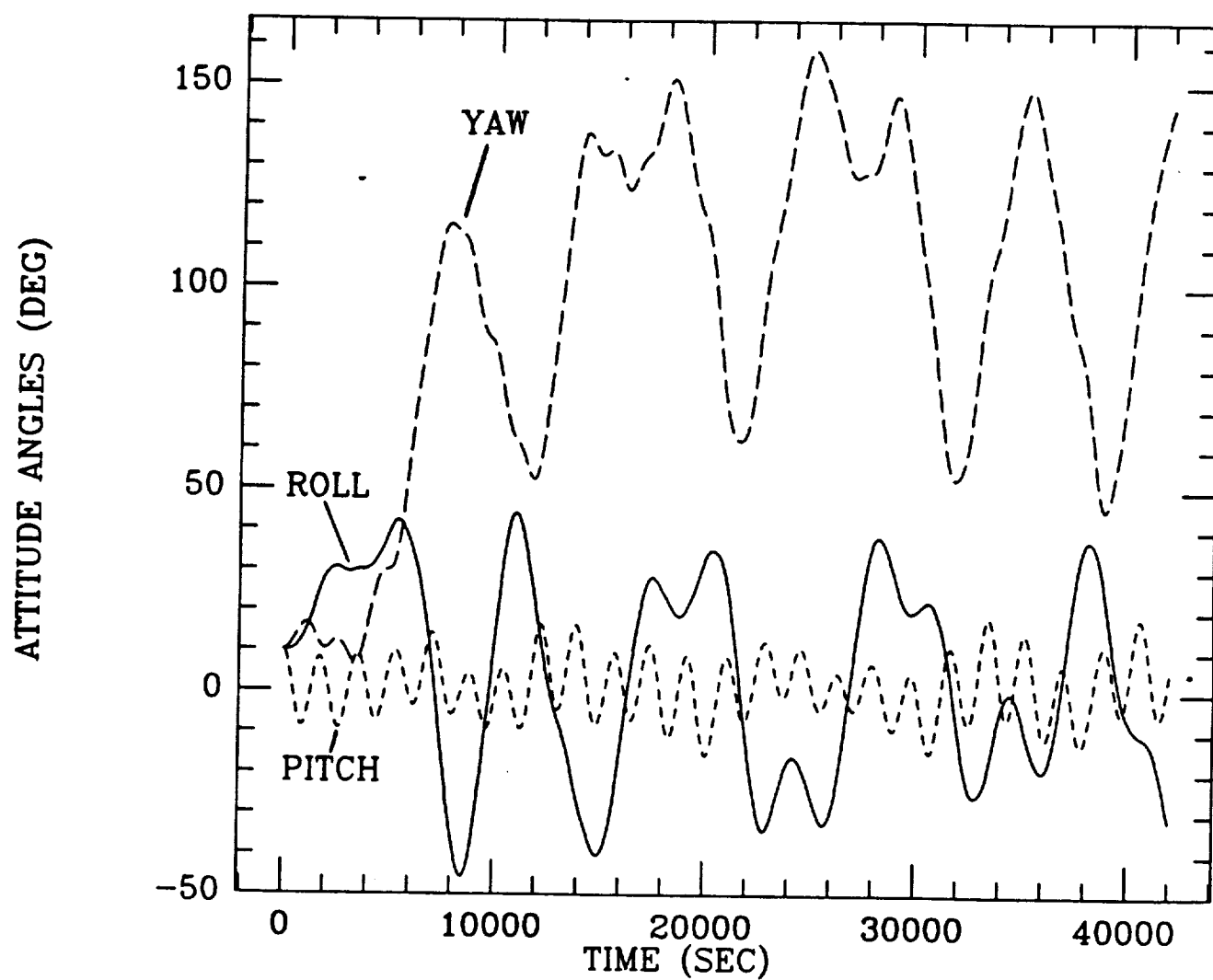


Figures 4.2(e)-(f)



Figures 4.2(g)-(h)

**Figure 4.2(1)**

**Figure 4.3**

